Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada

CLIMATE CHANGE RESEARCH

ASSESSMENT OF NET EMISSIONS OF GREENHOUSE GASES FROM ETHANOL-BLENDED GASOLINES IN CANADA: LIGNOCELLULOSIC FEEDSTOCKS

R-2000-2

JANUARY 2000

Canada

Cross-Sectoral Policy Development Division

Industry Performance and Analysis Directorate

Policy Branch, Agriculture and Agri-Food Canada

January 2000

Assessment of Net Emissions of Greenhouse Gases from Ethanol-Blended Gasolines in Canada: Lignocellulosic Feedstocks

R-2000-2

by:

Levelton Engineering Ltd.
150 - 12791 Clarke Place
Richmond, B.C.
V6V 2H9

in association with:

$(S\&T)^2$ Consultants Inc.

Editor: Stephen Henderson
Hendest@em.agr.ca
613 759-7382

EXECUTIVE SUMMARY

The agricultural and road transportation sectors are significant sources of greenhouse gas emissions in Canada. The agriculture and agri-food sector accounts for approximately 15% of Canada's annual emissions (roughly 14% can be attributed to primary agriculture with processing of food and fibre accounting for approximately another 1%). Emissions of greenhouse gases from Canadian road transportation sources in 1995 totalled approximately 123 Mt (Jaques et al, 1997). This amounts to about 19.9% of the total CO_2 equivalent greenhouse gas emissions from energy and non-energy sources in 1995 (23.8% if considering only energy sources) and about 74.3% of the total greenhouse gas emissions from the Transportation Sector. The greenhouse emissions from the road transportation sector arise 51.1% from automobiles, 26.0% from heavy-duty trucks and buses and 22.8% from light-duty trucks, with the remainder being from motorcycles.

In December 1997, the parties to the 1992 United Nations Framework Convention on Climate Change (FCCC) adopted a protocol to the Convention (the Kyoto Protocol) to limit emissions of greenhouse gases. The Protocol will come into force when fifty-five countries covering a minimum of fifty-five percent of the FCCC Annex 1 countries emissions, have ratified the protocol. Canada is an Annex 1 country and has accepted a GHG reduction target of six percent below its 1990 level of 564 Mt (CO_2 equivalents) by the end of the first reporting period, 2008-2012. Canada and a number of other countries have not yet ratified the Kyoto Protocol.

Analysis conducted by Environment Canada indicates that net GHG emissions in Canada will need to be reduced by 21-26 percent under a business-as-usual scenario to achieve the six percent reduction target. This is a difficult challenge for Canada given its growing population, cold climate, long transportation distances, and the fact that our exported raw materials contain significant embedded fossil fuel emissions.

The production and use of renewable fuels manufactured from lignocellulosic agricultural feedstocks, such as switchgrass and hay, or agricultural residues such as straw and corn stover is one greenhouse gas emission reduction opportunity that could offer a synergistic benefit to the agricultural and transportation sectors. A number of studies have been performed for the United States on the life-cycle greenhouse gas emissions of ethanol produced from switchgrass that have shown this fuel system has a positive energy balance and will result in a reduction in greenhouse gas emissions. This study was undertaken to provide an analysis of the life-cycle emissions and life-cycle energy balance of the production of ethanol from several agricultural lignocellulosic feedstocks and its subsequent use as a motor fuel in blends with gasoline. The study focuses specifically on Southern Ontario, an area with a large agricultural land base, as well as one with a large demand for motor gasoline. Energy and emission analysis was conducted in this study for a base case ethanol production volume of 225 ML per year in 2000 and 2010. Further analysis was done to investigate the effects of annual ethanol production volumes of 500 ML, 750 ML and 1,000ML. The analyses were performed for four feedstocks, switchgrass, hay, corn stover and wheat straw.

The crops switchgrass and hay provide the lowest greenhouse gas emissions due to their ability to sequester some carbon in the soil and in plant biomass over the alternative use of the land which was assumed to be unimproved pasture. The use of the agricultural residues, wheat straw and corn stover, was assumed not to provide any additional ability to sequester carbon over and above that which normally occurs due the production of the grain. It was assumed that sufficient fertilizer would be added to compensate for the removal of the residue, so that no reduction in soil carbon would occur.

For all of the feedstocks studied, ethanol produced and blended with gasoline will reduce emissions of greenhouse gases. The production of ethanol from corn stover in a full scale plant

and blended into gasoline, taking full advantage of ethanol's octane rating, reduces greenhouse gas emissions by 5.8% compared to gasoline. If a dedicated crop such as switchgrass is used as the feedstock, the reduction increases to 6.7%. The reductions in the year 2010 when the technology is expected to be fully developed increase to 6.2% for corn stover and 6.9% for switchgrass. Greenhouse gas emission reductions for E85 range from 57% for Ontario wheat straw in 2000 to 71.6% for switchgrass in 2010.

Some authors have reported the greenhouse gas emission reductions for just the ethanol portion of various blends compared to gasoline. To do this it is necessary to correct for the relative energy content of the ethanol. A 10% ethanol blend has 6.7% of its energy content supplied by the ethanol. The switchgrass near term E10 case therefore represents a 100% (6.7/6.7) reduction in greenhouse gas emissions for ethanol compared to gasoline. The E85 has 78.5% of its energy from the ethanol and thus it could be reported that for E85, ethanol represents a 90% (71.0/78.5) reduction in greenhouse gas emissions. The difference between E10 and E85 is caused by the relative efficiencies of the fuels in the combustion process. For all of the feedstocks considered for the year 2000 and the E10 blends the range in reductions in greenhouse gas emission for ethanol relative to gasoline is 80 to 100%. For E85 the range is 73 to 90%. For the year 2010 the range for E10 is 88 to 103% and for E85 it is 77 to 91%.

If ethanol production can be expanded to 1.1 billion litres per year by 2010 in plants processing corn stover, wheat straw and switchgrass then emissions of GHG can be reduced by 2.47 million tonnes annually. This represents 1.3 to 1.8% of the total reduction required to meet Canada's commitment to the Kyoto Protocol.

Producing ethanol has a net positive energy balance for most of the cases studied. The energy efficiency of the plants is expected to improve over the 2000 to 2010 time frame. There are a number of ways of measuring the energy balances for lignocellulosic ethanol. Many authors compare the fossil fuel inputs to the ethanol and electricity produced. On this basis 7 to 30 times as much energy is produced as fossil energy is consumed.

When all energy is considered including the energy in the feedstock that is burned to supply the plant energy requirements the energy balances are positive for the residues in 2000 on an effective energy basis and positive for all feedstocks in 2010.

Many of the practices modeled here are currently experimental and have not yet been demonstrated on a large scale. This would include the production and collection of some of the feedstocks as well as the production of ethanol from lignocellulosics. The best available data has been used for modeling and where possible it has been verified from multiple sources. The results projected here compare favourably to those projected by other authors.

Table of Contents

EXECUTIVE SUMMARY I

LIST OF TABLES V

LIST OF FIGURES V

LIST OF APPENDICES VI

LIST OF ABBREVIATIONS VII

1. INTRODUCTION 1
   - 1.1 BACKGROUND 1
   - 1.2 DESCRIPTION OF STUDY REGION 2
   - 1.3 SCOPE OF WORK 3

2. GENERAL APPROACH AND METHODOLOGY 4
   - 2.1 OVERALL APPROACH USED FOR STUDY 4
   - 2.2 OVERVIEW OF FULL CYCLE CONCEPT FOR GASOLINE AND ETHANOL BLENDS 4
   - 2.3 FULL CYCLE AND ENERGY BALANCE METHODS 5
     - 2.3.1 Greenhouse Gases Included 6
     - 2.3.2 Model Used to Calculate Full Cycle Emissions 6
     - 2.3.3 Gasoline 8
     - 2.3.4 Ethanol and Ethanol Blends 9
   - 2.4 FEEDSTOCK ANALYSIS METHODS 9
   - 2.5 MOTOR VEHICLE EMISSION ANALYSIS METHODS 10

3. LIGNOCELLULOSIC FEEDSTOCKS 12
   - 3.1 SWITCHGRASS 12
     - 3.1.1 Agronomic Data 12
     - 3.1.2 Land Use Assumptions 13
     - 3.1.3 Resource Supply and Disposition 14
   - 3.2 CORN STOVER 15
     - 3.2.1 Agronomic Data 15
     - 3.2.2 Land Use Assumptions 16
     - 3.2.3 Resource Supply and Disposition 16
   - 3.3 WHEAT STRAW 16
     - 3.3.1 Agronomic Data 16
     - 3.3.2 Land Use Assumptions 17
     - 3.3.3 Resource Supply and Disposition 17
     - 3.3.4 Western Canada Wheat Straw 17
   - 3.4 HAY 18
     - 3.4.1 Agronomic Data 18
     - 3.4.2 Land Use Assumptions 18
     - 3.4.3 Resource Supply and Disposition 19
   - 3.5 SUMMARY AND COMPARISON OF FEEDSTOCK DATA 19

4. ETHANOL PRODUCTION AND CO-PRODUCTS 21
4.1 PROCESS DESCRIPTION 21
4.2 CO-PRODUCTS AND DISPLACED EMISSIONS 22
4.3 ENERGY USE AND PRODUCTION 22
5. FULL CYCLE GREENHOUSE GAS EMISSIONS FOR ETHANOL, ETHANOL BLENDS AND GASOLINE 24
5.1 EMISSIONS AND ENERGY BALANCES FOR ETHANOL IN 2000 24
5.1.1 Greenhouse Gas Emissions for the Ethanol Production Cycle in 2000 25
5.1.2 Energy Balances for the Ethanol Production Cycle in 2000 26
Net Energy 27
5.1.3 Full Cycle Greenhouse Gas Emissions for 10% Ethanol Blends in 2000 28
5.1.4 Full Cycle Greenhouse Gas Emissions for 85% Ethanol Blends in 2000 29
5.1.5 Western Canada Wheat Straw 30
5.1.6 Summary for Year 2000 31
5.2 EMISSIONS AND ENERGY BALANCES FOR ETHANOL IN 2010 31
5.2.1 Greenhouse Gas Emissions for the Ethanol Production Cycle in 2010 32
5.2.2 Energy Balances for the Ethanol Production Cycle in 2010 33
5.2.3 Full Cycle Greenhouse Gas Emissions for 10% Ethanol Blends in 2010 34
5.2.4 Full Cycle Greenhouse Gas Emissions for 85% Ethanol Blends in 2010 35
5.2.5 Summary 36
5.3 THE POTENTIAL FOR LIGNOCELLULOSIC ETHANOL TO CONTRIBUTE TO MEETING CANADA'S COMMITMENT UNDER THE KYOTO PROTOCOL 39
6. SENSITIVITY ANALYSES, DATA GAPS AND UNCERTAINTIES 41
6.1 SENSITIVITY ANALYSES 41
6.2 DATA GAPS AND UNCERTAINTIES 42
7. CONCLUSIONS 43
8. REFERENCES 45

LIST OF TABLES

Table 1-1. Agricultural GHG Emissions for 1991. 1

Table 3-1. Comparison of Feedstock Data. 19

Table 5-1. Greenhouse Gas Emissions for the Production Cycle of Crude Oil and Ethanol in 2000. 25

Table 5-2. Energy Balances for Year 2000, Gasoline and Ethanol. 26

Table 5-3. Full Cycle Emissions of Greenhouse Gases for Gasoline and 10% Ethanol Blends for Various Feedstocks in 2000. 28

Table 5-4. Full Cycle Greenhouse Gas Emissions for Gasoline and E85 for the Year 2000. 29

Table 5-5. Comparison of Production cycle for Ethanol between Ontario and Western Canada Wheat Straw. 30

Table 5-6. Full Cycle Emissions of Greenhouse Gases for Gasoline and 10% Ethanol Blends from Ontario and Western Canada Wheat Straw in 2000. 31

Table 5-7. Greenhouse Gas Emissions for the Production Cycle of Crude Oil and Ethanol in 2010. 32

Table 5-8. Energy Balances for Year 2010, Gasoline and Ethanol. 33

Table 5-9. Full Cycle Emissions of Greenhouse Gases for Gasoline and 10% Ethanol Blends for Various Feedstocks in 2010. 34

Table 5-10. Full Cycle Greenhouse Gas Emissions for Gasoline and E85 for the Year 2010. 35

Table 5-11. Fuel Cycle Emissions of Individual Greenhouse Gases in 2000 and 2010 37

Table 5-12. Fuel Cycle Emissions of Individual Non-Greenhouse Gases in 2000 and 2010 38

Table 5-13. Summary of Predicated Results for 2010 Ethanol Production Scenario with a 10% Ethanol Blend 39

Table 7-1. Comparison of Results with those Reported by Wang and Delucchi. 44

Table B-1 Typical Crude Oil Slate for Southern Ontario 55

Table B-2 Greenhouse Gas Emissions for Crude Oil and Corn Production 56

LIST OF FIGURES

Figure 2-1. Full Cycle Including Fuel and Vehicle Cycles 5

Figure 2-2. Biomass to Ethanol and Petroleum to Gasoline Fuel Cycles 5

Figure 4-1. Iogen Process Schematic. 21

List of Appendices

Appendix A Supporting Data for Fuel Cycle Analysis 48
Appendix B Gasoline Production Chapter from Corn Ethanol Study 51
Appendix C Glossary of Refining Terms 59

List of Abbreviations

BTU	British Thermal Units Energy. To convert to kJ multiply BTU by 1.055
bu	Bushel
CAI	Commercial Alcohols Inc.
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 Equivalent	Weighted sum of CO_2, CH_4 and N_2O emissions using the weighting GWP factors defined below.
CPPI	Canadian Petroleum Products Institute
DDGS	Distillers dried grains with solubles. Also sometimes abbreviated as DDG.
E10, E85 & E100	10%, 85% and 100% ethanol with balance gasoline by volume, respectively
g	Gram
gal	US gallon (3.785 L)
GHG	Greenhouse gases
GJ	Gigajoule (10^9 Joules)
GWP	Global warming potential over a 100 year period: CO_2, 1; CH_4, 21; N_2O, 310
ha	Hectare (10,000 square meters)
HHV	Higher heating value of a fuel (combustion moisture as liquid)
K	Potassium fertilizer
k	Prefix for thousand
km	Kilometre
L or l	Litre
lb	Pound (0.4536 kg)
M	Prefix for million, when used with metric unit
mi	Mile (1.609 km)
MM	Million when applied to an imperial unit of energy
mpg	Mile per United States gallon
N	Nitrogen fertilizer
NMOG	Non-methane organic gases
NRCan	Natural Resources Canada
N_2O	Nitrous oxide
NO_x	Oxides of nitrogen
P	Phosphorus fertilizer
PJ	Petajoule (10^{15}J)
PM	Particulate matter
ppm	Parts per million by volume
SBM	Soy Bean Meal
SME	Soy methyl ester
S	Sulphur
SIE	Spark ignition engine
SO_2	Sulphur dioxide
t	Tonne (1000 kg)
THC	Total hydrocarbon
US	United States of America
USG	US gallons, (3.785 L)
VOC	Volatile organic compounds, excluding methane and ethane

1. INTRODUCTION

1.1 BACKGROUND

Under the Kyoto Protocol, Canada committed to reduce GHG emissions by 6% from 1990 levels by the period 2008 to 2012. The agriculture and agri-food sector accounts for approximately 15% of Canada's annual emissions (roughly 14% can be attributed to primary agriculture with processing of food and fibre accounting for approximately another 1%). Table 1-1 summarizes agricultural GHG emissions for 1991. Emissions data from Table 1-1 is from "The Health of Our Air" (AAFC, 1999) and the percentage of Canadian totals is derived from Jaques (1997) and the UN Framework Convention on Climate Change (UNFCC, 1999). Jaques reported N_2O emissions for agriculture at only 10% of those in The Health of Our Air and the UNFCC. Table 1-1 is derived from The Health of our Air and the UNFCC data. These numbers do not include emissions associated with the distribution of commodities from the farm to processing centres and ultimately to consumers; such emissions are attributed to the transportation sector.

Table 1-1. Agricultural GHG Emissions for 1991.

	Emissions Mt	Emissions CO_2 equivalent Mt	Percent of Canadian Totals
Carbon Dioxide	27.8	27.8	6.1
Methane	0.951	20.0	29.8
Nitrous Oxide	0.11	34.3	61.1
Total		82.2	14.1

Transportation represents the single largest source of Canada's GHG emissions, accounting for 27 per cent of the total. Transportation emissions arise from all sectors of the commercial economy and are inherent to the movement of people and goods for commercial, social and recreational activities. Hence, measures to reduce emissions from the transportation sector must be considered very carefully and respect the ramifications of such measures on the economy and peoples day-to-day activities. Emissions from transportation are growing faster than the average for all emissions and are forecast to exceed 1990 levels by 26 per cent in 2010 and 42 per cent by 2020 (NRCan 1997).

It is clear that both the transportation sector and the agriculture sector have significant roles to play in helping Canada meet its objectives under the Kyoto Protocol. One strategy that holds promise for both sectors is the production and use of renewable fuels manufactured from agricultural feedstocks.

Levelton (1999) recently completed a study for Agriculture and Agri-Food Canada entitled "Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario" which studied the conversion of corn to ethanol and blending of ethanol with gasoline. That study reported that full cycle greenhouse gas emissions for 10% ethanol blends could be reduced by 4.6 percent compared to gasoline by the year 2010. There is also interest in the production of ethanol from various lignocellulosic agricultural materials. Some studies have shown that these feedstocks can produce even greater greenhouse gas emission reductions than producing ethanol from corn although the technology is still in the development stages.

For a full-cycle analysis of greenhouse gas emissions for biomass ethanol the following types of emission sources need to be considered:

- manufacturing and distribution of fertilizers, herbicides, insecticides and fuels used for growing the biomass feedstocks;
- conversion of applied nitrogen fertilizer to N_2O and emissions associated with farming practices (tilling, irrigation, etc.);
- harvesting and collecting biomass;
- land use changes resulting from the production and removal of the biomass;
- ethanol plant energy use and co-product quantities and usage. Co-products associated with ethanol production from biomass include electricity and chemicals such as acetic and formic acids, and carbon dioxide;
- ethanol blending in gasoline and the effects on refinery energy efficiency if steps are taken to optimize refinery processes for ethanol;
- ethanol combustion in the motor vehicle fleet, with allowance for the effects on vehicle fuel economy.

There have been a number of published and unpublished studies of full cycle greenhouse gas emissions from the manufacture and use of biomass ethanol (Sheehan, 1998). These have mostly been done in an American context. The results from these studies have also varied widely, as the results are very sensitive to inputs, land use assumptions and methodology. It is therefore important to have a publicly accessible Canadian study that uses the best data available and applies sound scientific methodology to provide a basis for informed public policy decisions.

1.2 Description of Study Region

Southern Ontario is the region between the US border on the south, Quebec on the north and bounded by the Great Lakes on the east and west. This region of Canada is the major corn growing region, one of the most populated areas of Canada and is served by five oil refineries. It has Canada's largest fuel ethanol plant and fuel-ethanol marketing network.

The Southern Ontario region was chosen for the corn ethanol study because of feedstock availability. It also would have good availability of corn stover and there is considerable data available for the region on switchgrass and forage production. Focussing on this region also allows the extensive data developed on the refineries located in the region to again be used.

The Ontario market has the potential for substantially more use of ethanol than is currently being attained. If the ethanol is used as a 10% blend, the region has the potential to manufacture and use up to six times the ethanol that is currently being produced in the region. Significant market penetration of E85 vehicles or exports of ethanol could lead to even further growth in production and use.

It is important to fully understand the implications of expanded production of new crops, or the increased utilization of existing crop residues on the energy balances and greenhouse gas emissions associated with ethanol production.

1.3 Scope of Work

The objectives of the study can be summarized as follows:

1. Determine the lifecycle energy balance for the production of ethanol from four biomass feedstocks in southern Ontario. The feedstocks considered will be corn stover, wheat straw, switchgrass, and low protein hay. The analysis will take into account the energy credits for co-products from the ethanol production process, and be based on farming data for the Ontario region and operating and design data for logen's ethanol production process. As most of the data for wheat straw is from Western Canada, the significance of differences between the agronomic data for Ontario and the Prairies will be detailed.

2. Determine the impact on greenhouse gas emissions of using ethanol blended gasoline in blends of 10% and 85% compared to conventional gasoline. Emissions of carbon dioxide, methane and nitrous oxide will be considered for all aspects of the lifecycle from production through to end-use. The assessment will be quantitative and incorporate both feedstock production and gasoline refining/ethanol blending. Greenhouse gas emissions will be reported for individual gases and as combined CO_2 equivalent emissions.

3. Estimate energy balances for the specified ethanol blend cases for the year 2010 and relate the reduction in greenhouse gas emissions achieved in the future to Canada's commitment under the Kyoto Protocol.

4. Present the results of the study clearly using an analytical approach designed to accommodate analysis of specific scenarios of feedstock and size of the domestic fuel ethanol industry in Canada. Prepare a report in clear non-technical language that can be readily understood by decision-makers in government, and by ordinary Canadians.

2. General Approach and Methodology

2.1 Overall Approach Used for Study

The objectives of the study require the development of reliable estimates of the energy use and greenhouse gas emissions associated with production and use of four potential lignocellulosic feedstocks for ethanol production. With this information and the data developed in the corn ethanol study on refining and vehicle energy use and emissions, the net effect on energy consumption and greenhouse gas emissions of biomass ethanol-gasoline blends can be determined.

Lifecycle energy use and greenhouse gas emissions for gasoline are the reference for comparison in this study. We considered all stages in the lifecycle of gasoline from crude oil production, through to refining and use in a motor vehicle. The energy used for refining has been modeled considering the five refineries present in Southern Ontario and their typical crude oil supply mix. The methods used for the analysis are discussed later in this chapter. Also considered was the effect of the use of ethanol as a source of gasoline octane on the energy balance of a representative refinery in Southern Ontario.

The analysis is based on producing ethanol from lignocellulosic feedstocks in Southern Ontario and, hence, needs to consider the yield, farming practices and resource supply issues for this region. The feedstocks are presumed to be converted to ethanol using technology developed and being demonstrated by Iogen Corporation of Ottawa, Ontario. Data was obtained for this process with the co-operation of Iogen, allowing the analysis to model the energy use, product and by-product yields, and greenhouse gas emissions accurately.

This study considered two time frames, 2000 and 2010 and four ethanol production volume scenarios, 225 ML/yr., 500 ML/yr., 750 ML/yr. and 1,000 ML/yr. The potential reduction in greenhouse gas emissions was determined for each scenario based on the gasoline sulphur content appropriate for each time period. Trends in energy efficiency improvements have been included in the analysis for 2010.

2.2 Overview of Full Cycle Concept for gasoline and Ethanol Blends

The full cycle concept for analyses of energy and emissions considers all inputs into the production and use of a fuel. It combines the fuel production, vehicle manufacture and fuel use in a single analysis (see Figure 2-1.) It is also referred to as the fuel cycle by some authors. The ultimate result is a value that can be used for comparison of different commodities on the same basis, such as per unit of fuel energy or per kilometre driven. Greenhouse gas emissions over the full cycle include all significant sources of these emissions from production of the energy source (i.e. crude oil, biomass, natural gas, etc.), through fuel processing, distribution, and onward to combustion in a motor vehicle for motive power. A life cycle analysis should also include greenhouse gas emissions from vehicle material and assembly as these emissions are affected by the choice of alternative fuel/vehicle technology. Wide ranges of emission sources are involved in the production and distribution of fuels, and these vary depending on the type of fuel.

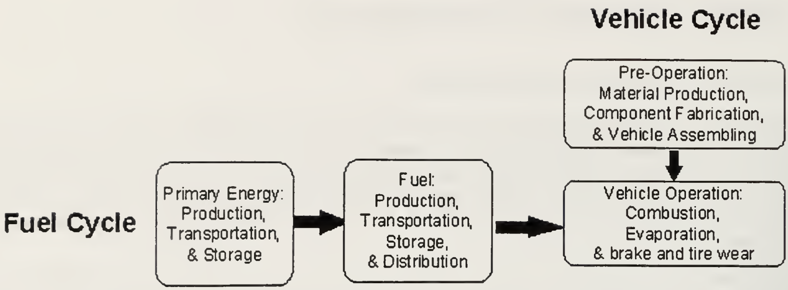


Figure 2-1. Full Cycle Including Fuel and Vehicle Cycles

The two fuel pathways of interest here are petroleum to gasoline and biomass to ethanol (Figure 2-2). The ethanol is subsequently blended with gasoline in various proportions. The final comparison is gasoline to ethanol blended gasoline.

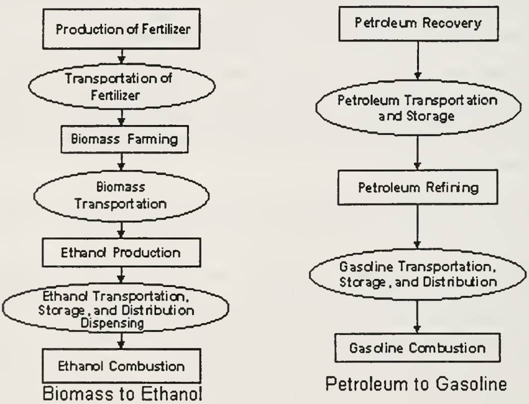


Figure 2-2. Biomass to Ethanol and Petroleum to Gasoline Fuel Cycles

2.3 Full Cycle and Energy Balance Methods

Two spreadsheet models are available from the United States to facilitate full cycle emission analysis; one developed by Delucchi (1991,1993, 1998), the other by Wang (1996). The work of Delucchi in the 1987-1993 period resulted in the development of a spreadsheet model based on Lotus software for Apple™ computers, which contained capabilities for predicting emissions of greenhouse gases and criteria non-greenhouse gases from most of the alternative fuels of

potential interest in this study. The model is comprehensive in scope and level of detail, and, hence, requires input of extensive information on the energy usage for fuel production, distribution and related fuel cycle sources, as well as factors for emissions of non-greenhouse gases from these sources and motor vehicles. Using the results from the Delucchi model and a simplified approach based on the application of energy conversion efficiencies and relative emission factors for emissions from the full cycle sources, Wang (1996, 1999) developed a user-friendly spreadsheet model for the US DOE in Excel™. This model is available on the Internet at www.anl.org.

Delucchi has updated his model since 1993, as described in Delucchi and Lipman (1996) and a report by Energy and Environmental Analysis Inc. (1999). This work has focused primarily on updating the earlier model to include recent data for motor fuel production, processing, distribution and use in the United States, and incorporation of improved algorithms for predicting non-greenhouse gas emissions from motor vehicles based on the U.S. EPA Mobile 5 model. A partial Canadianization of the Delucchi model was completed by Delucchi (1998) for Natural Resources Canada (NRCan) in late 1998 through to March, 1999, drawing from information on the production and distribution of conventional and alternative fuels that was provided by NRCan and Statistics Canada and some other Canadian government agencies.

The partially Canadianized version of the full cycle model prepared by Delucchi in 1998 was further developed by Levelton (1999b) for NRCan. This Canadianized version was used for the corn ethanol study and was selected for use as the starting point for this study. It was considered to yield the most rigorous life cycle analysis of both greenhouse and non-greenhouse gases from alternative motor fuels, and had the advantage of incorporating functional capabilities and data for analysis of Canada specifically. The parameters used in the model for predicting emissions from gasoline and ethanol production and use were further refined to accurately simulate full cycle emissions in the study area. The model utilizes the higher heating value (HHV) for the energy content of all fuels.

2.3.1 Greenhouse Gases Included

The greenhouse gases included in the calculations for this report are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The emissions have been weighted according to IPCC guidelines where CO_2 has a weighting factor of 1.0, CH_4 is assigned a value of 21.0 and N_2O has a weighting factor of 310. These are the 100-year global warming potential (GWP) multipliers recommended by the IPCC. Throughout the report we will report primarily CO_2 equivalent values. This will be the weighted sum of the three greenhouse gases. In some areas this will be further broken down to provide detail on the separate gases.

Other gases and contaminants associated with the production and use of fossil and renewable fuels, such as carbon monoxide, non-methane organic gases, oxides of nitrogen and particulates, also have the potential to influence climate change, either directly or indirectly. The global warming potential of these other gases has not been considered in this study, to be consistent with the approach being used by the National Climate Change Secretariat.

2.3.2 Model Used to Calculate Full Cycle Emissions

The Delucchi model, as used in this study, is capable of estimating fuel cycle emissions of the primary greenhouse gases, carbon dioxide, methane, nitrous oxide, and the criteria pollutants, nitrogen oxides, carbon monoxide, sulphur oxides, nonmethane organic compounds (also known as VOCs) and exhaust particulate matter. The model also is capable of analyzing the emissions

from gasoline and alternative fuelled internal combustion engines for both light-duty and heavy-duty vehicles, and for light duty battery powered electric vehicles.

The full cycle model predicts emissions for past, present and future years using historical data or correlations for changes in energy and process parameters with time that are stored in the model. The model is thus capable of analyzing what is likely to happen in future years as technologies develop. The model allows for segmentation of the predicted emissions into characteristic steps in the production, refining, distribution and use of fuels and the production of motor vehicles. The fuel cycle segments considered in the model are as follows:

- Vehicle Operation
  Emissions associated with the use of the fuel in the vehicle. Includes all three greenhouse gases.
- Fuel Dispensing at the Retail Level
  Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive emissions and spills.
- Fuel Storage and Distribution at all Stages
  Emissions associated with storage and handling of fuel products at terminals, bulk plants and service stations. Includes storage emissions, electricity for pumping, space heating and lighting.
- Fuel Production (as in production from raw materials)
  Direct and indirect emissions associated with conversion of the feed stock into a saleable fuel product. Includes process emissions, combustion emissions for process heat/steam, electricity generation, fugitive emissions and emissions from the life cycle of chemicals used for ethanol fuel cycles.
- Feedstock Transport
  Direct and indirect emissions from transport of feedstock, including pumping, compression, leaks, fugitive emissions, and transportation from point of origin to the fuel refining plant. Import/export, transport distances and the modes of transport are considered.
- Feedstock Production and Recovery
  Direct and indirect emissions from recovery and processing of the raw feedstock, including fugitive emissions from storage, handling, upstream processing prior to transmission, and mining.
- Fertilizer Manufacture
  Direct and indirect life cycle emissions from fertilizers, and pesticides used for feedstock production, including raw material recovery, transport and manufacturing of chemicals.
- Land use changes and cultivation associated with biomass derived fuels
  Emissions associated with the change in the land use in cultivation of crops, including N_2O from application of fertilizer, changes in soil carbon and biomass, methane emissions from soil and energy used for land cultivation.
- Carbon in Fuel from Air
  Carbon dioxide emissions credit arising from use of a renewable carbon source that obtains carbon from the air.
- Leaks and flaring of greenhouse gases associated with production of oil and gas
  Fugitive hydrocarbon emissions and flaring emissions associated with oil and gas production.
- Emissions displaced by co-products of alternative fuels
  Emissions displaced by electricity, a co-product of ethanol production, equal to emissions from electricity production displaced from other sources. Other co-products are calculated on the same displacement method.
- Vehicle assembly and transport

Emissions associated with the manufacture and transport of the vehicle to the point of sale, amortized over the life of the vehicle.

- Materials used in the vehicles
  Emissions from the manufacture of the materials used to manufacture the vehicle, amortized over the life of the vehicle.

Levelton (1999b) conducted a thorough review of the assumptions and characteristic parameters used in the original model to predict fuel cycle emissions from the fuels chosen in this study for detailed analysis. These assumptions and parameters were compared to information available to Levelton from in-house information, direct contact with energy and vehicle companies, published literature and other sources.

For the corn ethanol study further changes were made to the characteristics of the model to more accurately predict fuel cycle emissions in Ontario. A more in-depth review of land use changes, soil sinks and emissions, co-product credits and the implications of integration of ethanol into a refinery were made.

For this study further refinement of the model was undertaken to properly model the four feedstocks and to model a specific biomass to ethanol process rather than the generic process in the original model. This required an expansion of the number of co-products produced and calculations of the displaced energy from the production of those products. A summary of changes to the model and the input parameters is shown in Appendix A.

Fuel economy in units of miles per US gallon is the principal input variable available to the user of the model for case studies and is used within the model as the energy demand that must be satisfied by the fuel production, refining and other segments of the fuel cycle. Fuel economy values are input separately for city and highway travel and for light-duty and heavy-duty vehicles. The model inputs are all in US units. Most of the full cycle energy and greenhouse analyses found in the literature use US units. We have presented results in US units and in most cases present input data in metric and US units.

2.3.3 Gasoline

For the corn ethanol study the study team conducted a review of the Ontario refineries in terms of capacity, crude oil types processed, processing units employed and products produced. The greenhouse gases typically released during the production of the crude oil slate used in Ontario were calculated from published data from the Canadian Association of Petroleum Producers (CAPP 1998). The model was then calibrated to produce data consistent with the CAPP emission factors.

The energy used to make gasoline in a refinery that is representative of the plants in Ontario was determined from energy consumed by each refinery unit operated at an industry standard efficiency. This information was derived from the files of the study team and from interviews with Southern Ontario refiners. The study team also developed an estimate of the energy required for future gasoline production from analysis of the processing requirements.

Data from the foundation paper for the downstream petroleum industry, (Purvin & Gertz 1999) was used to verify the incremental refinery energy use in 2010 when low sulphur (30 ppm sulphur) gasoline will be required. Interviews with Canadian refiners provided insight into expected energy efficiency improvements in the refineries over the next decade.

Results were compared against published Canadian Refining Industry averages (Nyboer). No changes to the refinery data have been made for this study. The gasoline production chapter from the corn ethanol study is included as Appendix B.

2.3.4 Ethanol and Ethanol Blends

The study team worked with logen to develop the data required for the model inputs. logen have developed design data for a 225 million litre a year plant based on their research and design work for their demonstration facility. The study team was able to vet the data based on its experience with ethanol plant design and operation.

Ethanol blends were analyzed by incorporating ethanol at several levels into our typical refinery. Corrections were made to balance the octane produced at the refinery.

2.4 Feedstock Analysis Methods

An extensive literature search was undertaken to gather agronomic data for each of the four feedstocks considered in the study. US Departments of Energy and Agriculture databases were searched for relevant information. In addition data was gathered from Agriculture and Agri-Food Canada personnel. Discussions were held with the Ontario Corn Producers Association regarding corn stover.

One of the most important factors in modeling greenhouse gas emissions from ethanol production is forecasting whether the growth of the feedstock will impact on land use and result in changes to the amount of carbon stored either in the soil or in above ground biomass. The standard practice in cases where this is determined to occur is to amortize the change over some period between 15 and 25 years and apply an annual greenhouse gas emission to the crop. Delucchi (1998) details the methodology used in the fuel cycle model and Wang (1999) follows a similar but simpler calculation. The cases modeled here amortize above ground biomass over a 15 year period and below ground carbon changes over a 25 year period.

It is recognized that these land use impacts are reversible if the land reverts back to its original use. By applying a discount rate to these annual changes some credit or debit is given to these potentially temporary changes. With a discount rate of zero then no carbon value is given to these temporary changes, a large discount rate means little account is taken of the future reversion of current carbon changes. Delucchi uses a discount rate of 2% and that is used in both cases for this study. These assumptions result in 35% of the above ground biomass and 64% of the soil carbon changes being credited as carbon sequestration for the energy crops considered here.

Nitrogen applied as fertilizer can be converted to N_2O under certain conditions. The rate of conversion of applied nitrogen to N_2O is usually modeled as 1.3% (Delucchi, 1998) or 1.5% (Wang 1999). Agriculture and Agri-Food Canada (1999) reports a range of 0.1% to 1.6% depending on the type of nitrogen fertilizer applied. These results were based on laboratory tests. For the types of nitrogen applied to Ontario corn the weighted average would be 0.65%. For modeling purposes, we will use the higher loss rate (1.3%) as it is more accepted in the scientific community. The IPCC recommendation is for 1.25%. This is an area of uncertainty that can have a significant impact on predicted greenhouse gas emissions and we have chosen to model a slightly higher rate of loss than the IPCC guidelines to insure the results are conservative.

Delucchi allows for a carbon storage credit for nitrogen fertilizer that leaves the site as runoff. This nitrogen stimulates aquatic plant growth and stores carbon. It is quite a large factor and effectively offsets half of the N_2O emissions from fertilizer. We have not changed any of Delucchi's inputs in this area.

The cultivation of the soil can have an impact on the fluxes of carbon and methane between the soil and the atmosphere in addition to the nitrous oxide flows that were previously described. Soil organic carbon (SOC) is a function of tillage and residue management systems. Delucchi (1998) assumes that any cultivation results in decreasing SOC levels. He models a reduction of 0.1 kg C/m^2/year, which is at the low end of the range that he reports. We consider the impact of each crop separately. Factors such as the type of soil and previous use of the land are considered. It is recognized that Canada has been leading the International effort to better understand the potential role of agricultural soils as carbon sinks. The National Sinks Foundation Paper reports that by the year 2000 Canadian agricultural soils will shift from being a source of carbon to a sink.

There are also soil and methane interactions. Overall agricultural soils are a methane sink in Canada (AAFC 1999), but that is mainly due to well drained uncultivated soils (AAFC 1997). Well fertilized soils frequently inhibit methane oxidation and are sources of methane. Delucchi models methane emissions as a function of nitrogen applied (0.1 g CH_4/kg N) and as a function of area (25 g CH_4/ha/year). No changes to these parameters have been made.

2.5 Motor Vehicle Emission Analysis Methods

The primary emphasis of the study was on life-cycle energy balances and greenhouse gas emissions. The fuel economy of motor vehicles and the effect of ethanol on fuel economy are important inputs to the analysis. The impact of ethanol on vehicle fuel economy on an energy basis was determined from the literature.

Emissions of regulated pollutants such as carbon monoxide, nitrogen oxides, VOC's, particulates and sulphur oxides can be calculated by the model. The Delucchi methodology used is a simplified version of the Mobile 5 model developed by the US EPA. This model is in the process of being updated by the US EPA, and one of the most significant changes is with how the model deals with oxygenated fuels and carbon monoxide emissions. This change is being driven by the fact that Mobile 5 overestimates the reduction in ambient air levels of carbon monoxide that areas experience with mandatory oxygenated fuels programs.

Members of the study team ($(S\&T)^2$ 1999) have recently completed an analysis of the impact of ethanol on exhaust emissions in Canada. Data derived from that study has been used as inputs to the Delucchi model for ethanol blended gasolines. Carbon monoxide emissions and hydrocarbon emissions have been reduced by 15% for 10% ethanol blends. This actually produces more CO_2 from the ethanol blends as more carbon is oxidized during the combustion process. Emissions for E85 are assumed to be the same as for gasoline, although some manufacturers but not all have chosen to produce E85 vehicles that meet LEV exhaust standards. These more accurate model inputs create small differences in outputs compared to the corn ethanol study.

The fuel economy of E85 vehicles is assumed to be 5% better on an energy basis than gasoline based on real world experience with the vehicles (Wang 1999). The 1999 ethanol vehicle challenge reported results ranging from – 1 to +13% better than the comparable gasoline vehicle.

For E10 blends it is projected that the vehicles get a 1% better energy specific fuel economy. This is still about a 2.5% volumetric fuel economy reduction compared to gasoline. This projection is based on test data from the Auto/Oil Air Quality Improvement Research Program (Hochauser 1993) and recent test results from a program carried out by the Colorado Department of Public Health (Ragazzi).

There are a number of reasons to expect higher energy efficiency with ethanol blends. The lower emissions of carbon monoxide and hydrocarbons mean more energy from the fuel is released in the engine. In addition there are more moles of combustion products formed per mole of air for ethanol than for gasoline leading to higher pressures in the cylinder and finally the ethanol has a higher heat of vapourization than gasoline leading to lower intake tract losses and a cooler mixture.

3. Lignocellulosic Feedstocks

Four feedstocks were considered in this study. All are agricultural resources, however two can be considered crops (switchgrass and hay) and two can be considered residues (corn stover and wheat straw). Agronomic data for the study region (Southern Ontario) was determined from the literature. For the case of wheat straw data was also developed for the Western Canada Black Soil Zone.

In the cases of the residues it is assumed that demand for the residues will not cause additional planting of the primary crops and that any carbon sequestration above or below the ground is attributable to the primary crop and not the residue. The key data for developing the greenhouse gas emissions becomes the additional fertilizer requirements that are required to replace the removed nutrients and the fuel used for collecting the residue. Yield data is only important if it affects the energy required to collect the material and of course the amount of ethanol that can ultimately be produced. Yield data is important for the crops since it has an impact on the above ground carbon sequestration potential of the crop.

3.1 Switchgrass

Switchgrass is a summer perennial grass that is native to North America. Because it is native it is resistant to many pests and diseases and is capable of producing large amounts of biomass with low applications of fertilizers. It is reported (Bransby) to be tolerant of poor soils, drought and flooding. Switchgrass reaches full yield only in the third year after planting. Switchgrass stands can last ten years or more. It can be harvested in the spring or fall each year.

Switchgrass has been a major focus of the US Department of Energy's "Biofuels Feedstock Development Program". This program has more than twenty sites around the US raising switchgrass for research programs. In Canada Resource Efficient Agricultural Production-Canada (REAP), associated with Macdonald College at McGill University has been working with switchgrass for over ten years.

Typically, switchgrass is composed of 40% cellulose and 22% hemicellulose. Lignin content can range from 5-20%. It is projected to have an ethanol yield of 310 to 375 L/dry t in the Iogen process. The range results from the improvement in fermentation technologies expected over the next ten years. The low end of the range represents current expectations and the high end the expectations for 2010.

3.1.1 Agronomic Data

REAP (1999) recently reported on a three year study designed to develop economic, energy, and carbon data associated with switchgrass cultivation. The crop was grown at two sites in the Montreal area that were originally established in 1993. The Cave-in-Rock variety produced mean biomass yields of 12.4 t/ha (dry) over a three year period. Two other varieties (Pathfinder and Sunburst) produced yields of 11.6 – 12.0 t/ha. In the United States yields as high as 32 t/ha have been recorded in Alabama. One US program has a goal of breeding a switchgrass variety that will produce 22 t/ha in the Midwest corn belt where current yields are 11-15 t/ha.

Switchgrass trials in Western Canada have produced lower yields than those reported in Eastern Canada (Jefferson). This is not surprising in that switchgrass is a warm weather perennial and will respond favourably to heat. The greenhouse gas emission projections and energy balances developed in this report are only applicable to Southern Ontario and Quebec.

We have modeled harvestable switchgrass yields of 11.5 t/ha (5.1 T/ac). This is slightly higher than the 4.7 T/ac that Delucchi has previously modeled but is the lowest of the yields reported by REAP.

Switchgrass has lower fertilizer requirements than many crops. REAP applied 50 kg N/ha annually, at one site there was evidence of some yellowing of the crop which suggested that this was insufficient nitrogen. No other fertilizers were reported to have been applied by REAP. Oak Ridge National Laboratory in the US has developed a computer program "BIOCOST" (Walsh, 1996) to assist in determining the cost of producing switchgrass and hybrid poplar in seven regions of the US. The default fertilizer application rates in the program are nitrogen-N, 67.5 lb./ac switchgrass, and phosphorus and potassium are applied at the rate of 15 lb./ac and 25 lb./ac respectively. These rates are for an expected yield of 4.5 T/ac.

REAP measured the nutrient content of the harvested switchgrass both for a fall and spring harvest. For the fall harvest the nitrogen content was 0.46%, the phosphorus content 0.17% and the potassium content 0.95%. The fertilizer applied to the field should replace these minerals.

We have modeled fertilizer application rates based on the "BIOCOST" defaults of 7.5 kg/t N, 1.7 kg/t P and 2.8 kg/t K. The nitrogen rate is lower than that modeled by Delucchi but the other rates are all higher. No lime or sulphur is applied. With the exception of the potassium, which equals the harvest rate, these fertilizer rates do exceed the harvested nutrients. Since REAP achieved excellent growth results without any potassium or phosphorus fertilizers and less nitrogen, and we have modeled the case of the BIOCOST defaults, that is more fertilizer than used by REAP, we may be modeling a conservative case with respect to plant yield for the fertilizer applied.

REAP applied a herbicide only in the first year prior to planting at the rate of 2.0 kg/ha. BIOCOST is based on an annual application of herbicides. We have modeled herbicides being applied at the annual rate of 0.3 kg/t.

REAP report a fuel use of one USG of diesel per tonne of switchgrass harvested. This is about half that used by Delucchi in his modeling. The BIOCOST model does not explicitly state the default fuel consumption. It can be deduced from the output as 1.87 USG per Ton of switchgrass. We have used the BIOCOST default as it is based on a more intensive research program and probably more realistic of the real world than the REAP number. No gasoline or electricity is used. This value is also inline with the assumptions used for corn stover.

3.1.2 Land Use Assumptions

Switchgrass can be grown on marginal agricultural land or prime land. REAP reported slightly higher yields on a site that had a lower soil quality. In the US switchgrass has been considered a good crop for the CRP (Conservation Reserve Program) lands. Delucchi models a case where 80% of the switchgrass is grown on CRP land, 5% on deforested land, and 15% on generic agricultural land. These assumptions result in switchgrass providing more carbon sequestration below the ground and less above the ground compared to the current uses of the land. For Canada we do not believe that the deforestation option is realistic. In 1986 Ontario had 1.5 million hectares of unimproved farmland, which is about 25% of the total agricultural farmland in the province. This land is currently in the least intensive agricultural land use. There is no application of fertilizer and it is in continuous soil cover. It is therefore highly likely that through to the year 2010 unimproved farmland will supply all of the requirements for switchgrass. This is the case that we have modeled.

To calculate the above ground biomass the model calculates the biomass growth and adds the root mass by applying a scaling factor. The model default scaling factor for switchgrass is 1.02.

REAP measured root mass in their program and found that it was 68% of the above ground biomass. They report that this value was low compared to some US experience. We have adjusted the scaling factor to 1.68 based on the REAP data. The model now calculates an equivalent value for switchgrass of 1.0 kg C/m^2.

The model also requires the quantity of biomass produced on the land prior to planting the switchgrass. Delucchi reports a biomass content of 0.8 kg C/m^2 for CRP land based on data from an IPCC report. Typical yields of hay in Ontario are 6.6 t/ha (OMAFRA) we assume that on unimproved land yields will be 75% of that value or 5.0 t/ha. The ratio of total biomass to harvested yield for unimproved pastures is estimated to be 1.3 (Agriculture and Agri-Food Canada, 1999b). The total biomass currently produced is therefore estimated to be 6.5 t/ha or 0.3 kg C/m^2 and thus switchgrass is able to sequester carbon in the above ground biomass compared to the alternative of unimproved farm land.

Delucchi assumes that pasture land has soil with a carbon content of 6.8 kg C/m^2 and that land growing grass has a carbon content of 10 kg C/m^2. This results in the model calculating a considerable soil carbon sequestration benefit for grass. A review of the literature was undertaken to attempt to confirm the implied rate of carbon sequestration in the model.

The REAP study found that soil organic carbon levels dropped after 4 years of growth. REAP proposed several possible explanations to explain this unexpected result including the very high levels of soil carbon to start with, a possible lack of sufficient nitrogen addition to balance that removed by the crop and the possibility that carbon sequestration occurs in the later half of the growing cycle. REAP reports that other researchers have found that soil carbon can decline in the first years after crop establishment before carbon starts to accumulate although no references are given.

It would appear that Delucchi's estimates are overly optimistic. To develop more realistic projections assessments of the Canadian literature were relied upon. The Foundation Paper from the National Sinks Table (1998) reports that for intensively managed grasslands under the best management practices can sequester 0.02 kg C/m^2 per year over a twenty year period. We have set the model to emulate that rate of gain over 25 years and have set the difference in soil carbon content to 0.50 kg C/m^2 for the switchgrass and CRP land.

3.1.3 Resource Supply and Disposition

Switchgrass is not a commercial crop in Canada today. Iogen have contracted with some farmers to plant some 300 acres this year. The high yield and the ability to grow on marginal agricultural lands make it a potentially high volume resource. The 1.5 million hectares of unimproved farm land in Ontario has the capability of producing over 17 million tonnes per year of switchgrass. This is equivalent to over 5 billion litres of ethanol. While it is unlikely that all unimproved land would be converted to switchgrass and that the high yields modeled here could be achieved over all of this land even a small percentage of that land would create a substantial resource.

Given the novel nature of the crop the transportation distance to the ethanol plant is set to an average of 150 km. A 225 million litre a year plant will require 0.4% of the land within the assumed travel distance. This is a longer distance and a greater area than was modeled in the corn ethanol study. It is assumed that all feedstock is transported by truck to the ethanol plant.

3.2 Corn Stover

Corn stover is the above ground material left behind in the field after harvesting the grain corn. It is composed of the cobs, stalks, and leaves of the plant. It is a potentially attractive resource due to the quantities available. Corn is one of the most efficient photosynthetic plants known. It does require high heat input so it is not suitable for all regions of Canada. A high proportion of the corn grown in Canada is grown in Ontario and Quebec, the region considered in this study.

The composition of stover is typically 44% cellulose, 26% hemicellulose and 15-20% lignin. In the Iogen process it is expected to yield 345 L/dry t with current technology and 420 L/dry t in the year 2010.

3.2.1 Agronomic Data

The yield of corn stover is generally accepted to be equal to the quantity of corn harvested (Glassner 1998). This is an estimate since very little corn stover is harvested. Other researchers including REAP have reported more non-grain biomass than grain corn and ratios up to 1.2 can be found in the literature (Lindley). Using the ratio of 1.0 the situation in Ontario with corn yields of 116 bu/acre and 15% moisture this would equate to corn stover yields of 2.51 dry t/acre or 6.19 dry t/ha. The corn stover yield does not impact carbon sequestration since we are assuming that the amount harvested does not directly impact the soil carbon content or the quantity of biomass produced. Nutrients will be added to the soil to make up the nutrients removed. Those nutrients will impact greenhouse gas emissions.

Corn stover is either incorporated into the soil in conventional tillage operations or shredded and left to decompose on the surface in no till operations. In either case most of the carbon is oxidized within a year and returned to the atmosphere as carbon dioxide. Small amounts are harvested for cattle feed. A comparison of soil organic matter between grain corn grown with conventional tillage and corn silage where most of the above ground biomass was removed showed no differences over a thirty year period (Reicosky 1998). In actual practice it is difficult to remove all of the stover and the practical maximum removal rate is 60-70% of the above ground material leaving all of the root system and significant quantities of biomass for soil conservation. Root mass is equal to about 10% of the total biomass for corn.

The corn stover does return some nutrients to the soil when it decomposes. We will assume that extra fertilizer must be added to the corn crop to compensate for the removal of the nutrients. The fertilizer value of corn residues have been reported to be (Tyson 1992) 9.4 kg/t of stover for nitrogen, 1.5 kg/t for phosphorus, and 11.2 kg/t for potash. It will be assumed that all of the extra fertilizer required will be from chemical sources as all of the manure is currently being utilized for existing crop production. This calculation assumes that the nutrients in the straw are as effective as chemical fertilizers.

There are no additional pesticide requirements for corn crops if the stover is removed from the field also.

Delucchi has estimated that collecting and baling corn stover requires 2 USG of diesel per ton of residue collected based on similar collection practices to switchgrass. Glassner and Tyson do not report fuel consumption but rather report the operating costs for harvesting and baling corn stover. Their costs are generally consistent with Delucchi's fuel consumption estimate. It is likely that this diesel consumption is slightly high since switchgrass would also require a fertilizer application that would use a small amount of diesel fuel. To be conservative we will use Delucchi's estimate.

3.2.2 Land Use Assumptions

The production and utilization of the corn stover is incidental to the production and harvesting of corn. It is therefore not appropriate to include a credit or debit for above ground biomass or for below ground carbon changes unless these changes are directly related to the removal of the stover from the system. The data presented by Reicosky suggests that there are no soil organic carbon impacts of removing 70% of the stover. If the fertilizer requirements for the corn crop are adjusted for the removal of the nutrients in the stover then there should be no corn yield changes and thus no changes in aboveground biomass produced.

The model parameters are set to reflect no carbon changes in the above or below ground systems. There are still some emissions associated with land use since some nitrogen fertilizer is used and some of this will be converted to N_2O and some will run off the site and stimulate biomass growth of the field.

3.2.3 Resource Supply and Disposition

The quantity of corn stover available in Ontario and Quebec is calculated based on the corn production, the stover to corn ratio and the 70% proportion of stover that can be collected without negatively impacting soil quality. The Ontario quantity is estimated to be 3.0 million tonnes with a further 1.7 million tonnes available in Quebec. With a projected ethanol yield of 345 to 420 L/dry t the combined total is sufficient to produce 1.6 to 2.0 billion litres of ethanol per year.

A market for corn stover would be a new opportunity for farmers. It is likely to take some time before the harvesting and collection of stover becomes a common practice. To account for this larger transportation distances between the farm and the ethanol plant have been modeled. In the year 2000 an average transportation distance of 150 km is used. This is double the distance modeled for corn and thus provides for a collection area of four times that of corn for a similar sized plant. A 225 million litre per plant will require stover to be collected from 0.9 % of the land within the area defined by the 150 km distance. It is assumed that all of the stover will be transported by truck.

3.3 Wheat Straw

Wheat straw is a potential agricultural residue feedstock for ethanol production. The production of wheat does not produce the same high yields as corn either in terms of grain or biomass. It provides an interesting alternative to corn stover and provides a sensitivity case for agricultural residues. It would be a very significant resource in Western Canada.

Wheat straw has a composition of 47.5% cellulose and 19% hemicellulose. Ethanol yield from the Iogen process will be 330 L/dry t in 2000 and 400 L/dry t in 2010.

3.3.1 Agronomic Data

Winter wheat is the predominant wheat crop in Ontario. Wheat yields have averaged 4.3 t/ha over the past three years (OMAFRA 1999b). Residue yields ranging from 1.3 to 1.7 times grain yields have been reported (Tyson and Lindley). We will assume a factor of 1.3 and further that part of that is chaff, we will assume that the straw to grain ratio is 1.0. This equates to production of 4.3 t/ha or 70% that of corn stover.

In Ontario wheat straw today is either incorporated into the soil or collected and used for animal bedding. When it is returned to the soil it does provide for some nutrients. These nutrients have

to be replaced by fertilizers if the straw is removed. The fertilizer value is reported to be 18.3 kg/t for nitrogen, 3.3 kg/t for phosphorus and 31.7 kg/t of potassium (OMAFRA 1999c). Compared to corn stover it is more nutrient dense. We model the case where all of the nutrients removed are replaced by chemical fertilizers. Alberta Agriculture (1999) reports lower values for wheat straw in Western Canada with 6 kg/ dry t for N, 1.85 kg/dry t for P and 15 kg/dry t for K. Alberta suggests that over a three year period all of these nutrients are taken up by new growth and that the practice of determining the value of straw based on the fertilizer equivalents is a reasonable one.

There are no additional pesticides for wheat crops if the straw is removed.

The energy required to collect and bale the wheat straw is reported (Tyson) to be similar to that required for corn stover. Coxworth (1999) suggests that the energy required for baling and loading straw is 1.83 l/t straw. This seems more reasonable than Tyson's value and thus we model the case where 0.45 USG/Ton used for collection, baling and loading onto a truck.

3.3.2 Land Use Assumptions

Like corn stover the production and utilization of wheat straw is incidental to the production and harvesting of wheat. It is therefore not appropriate to include a credit or debit for above ground biomass or for below ground carbon changes unless these changes are directly related to the removal of the straw from the system. If the fertilizer requirements for the wheat crop are adjusted for the removal of the nutrients in the straw then there should be no wheat yield changes and thus no changes in aboveground biomass produced.

The model parameters are set to reflect no carbon changes in the above or below ground systems. There are still some emissions associated with land use since some nitrogen fertilizer is used and some of this will be converted to N_2O and some will run off the site and stimulate biomass growth of the field. Wheat straw has a higher nitrogen content so these emissions are higher than they are for corn stover.

3.3.3 Resource Supply and Disposition

There have been about 300,000 ha of winter wheat grown in Ontario the last several years (OMAFRA 1999b). This produces about 1.3 million tonnes of straw. Using the same 70% recovery factor as for corn stover there are 0.9 million tonnes of recoverable straw produced in Ontario annually. With a projected ethanol yield of 330 to 400 l/t this resource would produce 300 to 360 million litres of ethanol per year. A large portion of this straw is currently used for animal bedding leaving a relatively small quantity available for ethanol production.

The same 150 km trucking distance has been used for wheat straw as the other feedstocks considered.

3.3.4 Western Canada Wheat Straw

There is a much larger resource availability of wheat straw in western Canada. The wheat yields are much lower in western Canada than in Ontario but the land devoted to wheat production is much higher. Straw yields of 1.2 to 3.0 t/ha have been reported (Stumborg 1995) with an average of 1.18 t straw per t grain. The area of wheat grown has averaged about 12 million hectares in the 1990's (Manitoba Rural Adaptation Council). This would suggest wheat straw production of about 29.5 million tonnes per year. Existing uses for the straw include animal bedding, soil erosion protection, and inclusion in the soil to maintain soil carbon levels.

The literature was reviewed to determine if there are significant differences in the resource that would affect the greenhouse gas emissions. The primary factors that would influence GHG emissions are the nutrient levels in the straw and the energy used to collect and bale the straw. The yield of straw per hectare does not enter into the calculations of greenhouse gas emissions directly. Fertilizer inputs in the model are on the basis of pounds of fertilizer per ton of feedstock. Energy used for production and harvesting is on the same basis. The only differences in emissions between Ontario wheat straw and Western Canadian wheat straw would be from differences in nutrient levels and differences in energy required for harvesting. Ontario straw appears to contain more nitrogen, which would cause higher emissions. A sensitivity case will be run using Western Canada wheat straw nutrient levels to determine the magnitude of the impact of lower nutrient levels on greenhouse gas emissions.

Cereal residues available for ethanol production in Western Canada beyond what is currently being used for animal bedding, and what is required for soil conservation were estimated to be at least 2 million tonnes in a low yield year and averaging 8 million tonNes over 10 years (Stumborg). This resource would be capable of producing 700 to 2800 million litres of ethanol per year.

3.4 Hay

There are about one million hectares of land in hay production in Ontario. This land typically produces seven to eight million tonnes of hay annually. Varieties that may have potential for ethanol production include bromegrass, reed canarygrass and timothy hay. These varieties have a low protein content and higher fermentables than varieties such as alfalfa hay. The production is generally lower than that of switchgrass but it is an existing crop with much more data available.

The composition of the hay varies with variety. Timothy hay appears to have one of the highest fermentables contents. It can be expected to contain 40% cellulose and 22% hemicellulose. Ethanol yields from timothy hay in the Iogen process are expected to be 305 L/dry t in 2000 and increasing to 370 L/dry t in 2010.

3.4.1 Agronomic Data

The yield of all hay crops in Ontario averages 7.26 t/ha (OMAFRA 1999). McElroy (1997) reported that yields of bromegrass, orchardgrass, reed canarygrass and timothy hay averaged 8.4 t/ha in southern Ontario and 6.5 t/ha in northern Ontario. The test plots were managed under a low input, single-cut management system such as would be used to produce feedstock for ethanol production.

The fertilizer requirement has been modeled at 7 kg/t N (AAFC 1999b). In consideration of the low inputs no additional phosphorus or potassium has been added. The fuel requirements for hay are 20 litres per acre (AAFC 1999b) or 1.76 USG/T a number that is generally consistent with that used by Delucchi for switchgrass. Herbicide usage for hay crops was reported to be 0.006 kg/t hay (Hunter) for the year 1998. That value has been incorporated into the model.

3.4.2 Land Use Assumptions

The alternative use for the land used to grow the hay will be the same as assumed for switchgrass, unimproved pasture. The natural biomass levels are the same as assumed for the switchgrass cases. With the addition of some fertilizer creating higher yields for hay compared to unimproved pasture, there is some sequestration of carbon in the biomass. The same

assumptions regarding soil carbon sequestration will be made for hay as for switchgrass. That is 0.02 kg C/m^2 per year.

3.4.3 Resource Supply and Disposition

The potential for increased hay production lies with the utilization of the 1.5 million hectares of unimproved farm land in Ontario. The biomass potential with hay is less than switchgrass because of the lower yield. Production potential is 10.9 million tonnes of hay and with an ethanol yield of 305 to 370 L/dry t the ethanol potential from this resource is 3.3 to 4.0 billion litres per year.

Transportation distances to the ethanol plant are assumed to be the same as the other feedstocks modeled (150 km). All feedstock will move to the plant by truck

3.5 Summary and Comparison of Feedstock Data

It is useful to compare the agronomic data and land use assumptions for the four feedstocks under consideration and the data on corn developed in the previous study. The data is presented in Table 3-1 with the corn data converted to consistent units with the lignocellulosic feedstocks.

Table 3-1. Comparison of Feedstock Data.

	Corn	Switchgrass	Corn Stover	Wheat Straw		Hay
				Ontario	Western Canada	
Yield, t/ha	6.19	11.5	6.19	4.3	2.2	7.26
Nitrogen Fertilizer, kg/t	22.6	7.5	9.4	18.3	6.0	7
Phosphorus Fertilizer, kg/t	7.4	1.7	1.5	3.3	1.85	0
Potassium Fertilizer, kg/t	9.9	2.8	11.2	31.7	15	0
Pesticides, kg/t	0.21	0.3	0	0	0	0
Energy for production, USG diesel/t	3.39	2.06	2.2	0.45	0.45	1.94
Soil Carbon Changes, kg C/m^2/yr	-0.002	0.02	0	0	0	0.02
Biomass Changes, kg C/m^2	0.58	0.7	0	0	0	0.08
Projected ethanol yield 2000, L/dry t	470	310	345	330	330	305
Projected ethanol yield 2010, L/dry t	475	375	420	400	400	370

Several facts become apparent from Table 3-1. The first is the photosynthetic efficiency of corn compared to some of the energy crops under consideration. This is probably due in part to the fertilizer applied, which is far higher than that required by switchgrass or hay. The agricultural residues, particularly wheat straw, have significant fertilizer value. This will increase the value of the resource to the producer and make these crops less attractive as a low cost feedstock. There

is a wide variation in the energy required for production of the crops. The corn value includes some energy for drying, which has not been included in any of the other feedstocks.

4. Ethanol Production and Co-products

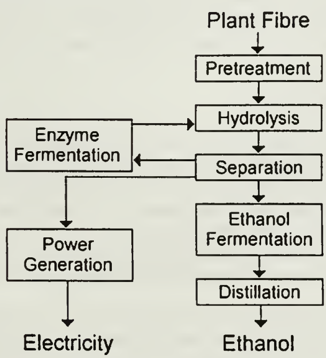
The conversion of lignocellulosic material to ethanol is a developing technology. There are not any plants operating on a stand-alone basis in North America today. There are several pulp mills that produce ethanol from wood sugars as part of the effluent treatment process for sulphite pulp mills. To model this process data has been obtained from one of the process developers in the field. The Delucchi model is capable of modeling this process. Delucchi relies on design data developed by the National Renewable Energy Laboratory in the US. The model results for this process are not as robust as those for other processes that are in commercial production. We have used the best data available for the modeling.

4.1 Process Description

Iogen Corporation of Ottawa is a world leader in the field of ethanol production from lignocellulosic materials. They are currently constructing a 50 tpd demonstration plant in Ottawa. That facility is expected to be completed and ready for commissioning in April 2000. It is built on the site of Iogen's existing research facility and enzyme manufacturing plant.

The Iogen process is known as an enzymatic hydrolysis process in which enzymes are used to convert cellulose and hemicellulose to fermentable sugars. Prior to the hydrolysis the feedstocks are pre-treated with a modified steam explosion step to increase the accessibility of the fibre so that fewer enzymes are required for the hydrolysis step. After pretreatment the substrate passes to hydrolysis vessels for conversion of the cellulose and hemicellulose fibres to glucose and pentose sugars. A portion of these sugars is used to produce the enzymes for hydrolysis and the remainder is sent to the fermenters for conversion to ethanol. Iogen are working with other researchers to develop better organisms for the conversion of pentose sugars to ethanol. For modeling purposes we have assumed that in 2000 75% of the pentose is convertible to ethanol and that by 2010 all of the pentose sugars are convertible to ethanol. The process schematic is shown in Figure 4-1.

Figure 4-1. Iogen Process Schematic.



Iogen removes the lignin and other non-fermentables from the process and burns that material to produce steam and electricity for the plant. There is sufficient material available to supply all of the plant energy requirements and to produce some electricity for sale.

The ethanol recovery step uses similar distillation technology as is used in existing grain based ethanol plants.

Data supplied by logen was developed for the construction of their demonstration plant.

4.2 Co-products and Displaced emissions

The primary co-product from the process is electricity. logen will also produce and recover a small amount of acetic acid from the process. The quantity of electricity produced is dependent on the ethanol yield. A larger quantity is produced in 2000 when not all of the sugars can be converted to ethanol. As sugar conversion capability improves the quantity of electricity produced decreases. In 2000 we have modeled 1.52 kWh/USG of ethanol for corn stover and for wheat straw based on input from logen. For the switchgrass and hay with the lower ethanol yield and more non-fermentables available for combustion we have increased the amount of electricity available to 1.9 kWh/USG of ethanol. We have decreased the amount of electricity produced by 3% per year so that in 2010 electricity drops to 1.12 kWh/USG for straw and stover, which is logen's projection. For switchgrass and hay the electricity production in 2010 is 1.40 kWh/USG of ethanol. The quantity of acetic acid produced is 3% of the plant feed.

The co-product credits are calculated on the basis of emissions displaced from the products that they replace. In the case of electricity, production from an ethanol plant will displace the marginal source of electricity production in that province. In most provinces, including Ontario, natural gas is the marginal fuel for electricity production. The greenhouse gas emission credit for electricity from an ethanol plant is therefore calculated on the basis of the emissions that would have occurred if that electricity had been produced from natural gas.

For the production of acetic acid the displaced emissions are calculated based on recommendations from the Office of Industrial Technology, US Department of Energy. The energy required for acetic acid production is reported to be (OIT, 1999) 18,000 BTU/lb. This is further broken down to 6,250 BTU of chemical energy and 11,700 BTU of process energy. logen has not yet calculated the energy requirements for extracting the acetic acid so we have assumed that this energy is already incorporated in the electricity generated, and have only assumed a credit for the chemical energy in the acetic acid. One ton of feedstock will produce 60 pounds of acetic acid that will displace 0.375 million BTU. It has been assumed that the energy for the US case was supplied by natural gas. Delucchi has not modeled this co-product.

4.3 Energy Use and Production

The plant is self sufficient in steam and electricity requirements. The production of surplus electricity is dealt with as a co-product. The plant will require some diesel fuel to operate mobile equipment at the site to offload and move around the feedstock. Delucchi uses 0.008 USG diesel/USG ethanol. We will also use that figure. The feedstocks under consideration all have relatively high amounts of ash. It will be assumed that 10% of the plant feed will end up as ash and non-combustibles and have to be transported 10 miles to a landfill. These energy requirements and greenhouse emissions will be subtracted from the co-product credit.

Even though the plant uses biomass for energy production and thus has no net CO_2 emissions from this stage there are still greenhouse gas emissions of methane and nitrous oxide from the combustion of the lignin. Delucchi calculates these emissions from data from the US DOE's National Renewable Energy Laboratory.

We have modeled the plant to include its own enzyme production, thus the energy requirements and yield impacts of that manufacturing step is included in all of the greenhouse gas calculations

and end energy balances. The major materials input to the ethanol plant are sulphuric acid and lime at 1% by weight of the feed to the plant.

In calculating the energy balances for fuels that use the same feedstock for production and energy supply, Delucchi bases the input energy on the higher heating value of the feedstock. For cases such as ethanol production from lignocellulosics this overestimates the energy used in the plant as it includes the chemical energy present in the product. Some of the feedstock energy in the form of sugars is consumed by the organisms to produce enzymes and by the yeast to produce ethanol. This energy is not available for use in the plant. In the case of the corn ethanol plant the energy balance is calculated from the natural gas and electricity inputs and not from the chemical energy in the corn.

We have followed a methodology similar to that used for corn ethanol and for gasoline production. That is we have estimated the quantity of biomass used for energy production in the plant. The basis for the estimates is first to calculate the quantity of non-fermentables in the feedstock. This is the total dry weight less the mass of cellulose and hemicellulose. It is recognized that in addition to this there will be some cell mass from dead yeast and the spent organism for producing enzyme and some non-fermented sugars that goes to the boiler. To estimate this we have calculated one half of the difference between actual ethanol production and theoretical ethanol production and added this to the mass that is burned. The heating value of this fuel is assumed to be 9250 BTU/lb from estimates of the heating value of hardwood lignin residues from an acid hydrolysis process (Blunk, 1999). Iogen have found similar values from their tests.

5. Full Cycle Greenhouse Gas Emissions for Ethanol, Ethanol Blends and Gasoline

Two different ethanol blends were analyzed, low-level blends of 10% ethanol and a high-level blend containing 85% ethanol (E85). The low-level blends are capable of being used in all current vehicles interchangeably with existing gasolines. Blends of 6 to 10% ethanol have been sold in Ontario by Sunoco for a number of years and 10% ethanol blends have been sold by Mohawk Canada in Northern Ontario and Western Canada since the 1980's. All automobile manufacturers accept gasolines containing up to 10% ethanol. Gasolines that contain more than 10% ethanol may cause excessive enleanment of the air fuel mixture and result in driveability problems. These fuels are not approved by auto manufacturers for use in gasoline powered vehicles. The E85 fuel analyzed is used in vehicles designed to accept high levels of ethanol in gasoline. These flexible fuel vehicles may also operate on 100% gasoline. Ford and DaimlerChrysler currently sell flex fuel vehicles capable of using E85.

The use of ethanol for the production of low-level gasoline blends can be incorporated into the Ontario refineries using the existing flexibility of those facilities. The plants have the flexibility to incorporate as much as 13% ethanol into the gasoline (if they were accepted in the market place) and still meet the requirements of the diesel fuel market. The high octane content of the ethanol will allow some energy savings in the refinery and this has been built into the modeling in the form of reduced refining energy for the low level blend cases.

E85 is sufficiently different to be considered as a new fuel rather than a gasoline blend. Significant quantities of low-level blends and E85 would exceed an individual refinery's flexibility to adjust the gasoline and diesel production ratio. Consequently, the E85 scenarios considered in this study do not allow any energy savings within the refinery.

For the analyses of future years we have followed the improvement rates used by Delucchi (1999) for all assumptions except the energy use in the refinery and the ethanol plant. For the refinery we have assumed that the energy efficiency improves by 1.0% per year until 2001 and by 0.5% per year after that until 2010. This is the same assumption used by Levelton in the original Canadianization of the model and is based on the energy consumption targets set by the Canadian Petroleum Products Institute (Purvin & Gertz, 1999). Overlaid on this improvement is a specification change for gasoline with the sulphur content dropping to 30 ppm by 2005. This will require a significant increase in energy used in the refinery. For the ethanol plant, we have increased the ethanol yields based on expectations by Iogen. The electricity production rate drops due to the increased conversion of sugars to ethanol again at the rate expected by Iogen. This is the opposite of Delucchi's assumption about increasing outputs of ethanol and electricity. This can happen only if there is a significant reduction in the energy use in the plant.

The ethanol production improvements that have been modeled do rely on continued technology development with respect to cellulose and hemicellulose conversions to ethanol. There is considerable effort being made in this field in Canada and the US by Iogen and others. It is reasonable to expect the improvements can be achieved.

5.1 Emissions and Energy Balances for Ethanol in 2000

Each of the feedstocks were run in the model to determine energy balances and greenhouse gas emissions. The results for the ethanol production cycle are presented first to highlight the differences that the feedstock creates.

5.1.1 Greenhouse Gas Emissions for the Ethanol Production Cycle in 2000

The Delucchi full cycle model was run for the year 2000 for each of the feedstocks of interest as well as for gasoline and corn ethanol for comparison purposes. The results for the ethanol production cycle are shown in Table 5-1. All of the ethanol totals do not include the emission credit for the use of a renewable source of carbon for the ethanol production. The gasoline total does not include the emissions from end use.

Table 5-1. Greenhouse Gas Emissions for the Production Cycle of Crude Oil and Ethanol in 2000.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer
Fuel Dispensing	160	165	165	165	165	165
Fuel Storage and Distribution	774	1,534	1,534	1,534	1,534	1,534
Fuel Production	8,755	38,927	6,477	7,246	7,439	7,803
Feedstock Transport	371	1,588	4,732	4,253	4,446	4,810
Feedstock Recovery	8,219	8,912	5,572	6,044	1,956	6,835
Land Use Changes	0	908	-7,247	2,550	4,692	-4,915
Fertilizer Manufacture	0	6,654	5,301	5,227	12,090	4,055
Leaks and Flares	1,821	0	0	0	0	0
Emissions Displaced by Co-products	0	-12,771	-13,775	-11,331	-11,460	-13,827
Total	20,200	45,917	2,758	15,688	20,862	6,460

The greenhouse gas emissions from ethanol produced by lignocellulosics are all less than the emissions from corn ethanol production. The primary reason for this is in the production of the ethanol where the use of the lignin as a fuel is substituted for the natural gas used for corn ethanol production. Feedstock transport emissions are higher for the lignocellulosic feedstocks due to the lower yields and longer transportation distances assumed than for corn. The fertilizer emissions from corn and the other feedstocks are not directly comparable since one third of the nitrogen fertilizer for corn is supplied by manure and all fertilizer for the lignocellulosic feedstocks are from chemicals which have a higher emissions per unit of fertilizer. The Ontario wheat straw with its high level of nutrients has the highest fertilizer requirements.

The differences in land use emissions arises from the assumption that stover and wheat are by-products of grain production and the harvesting and use of those materials does not cause any changes in soil carbon or biomass growth to offset the emissions of N2O from the fertilizer applications. The ability of switchgrass and hay to sequester carbon in the soil and in biomass results in the lowest full cycle greenhouse gas emissions for those feedstocks in spite of the fact that they have the lowest ethanol yield.

5.1.2 Energy Balances for the Ethanol Production Cycle in 2000

The energy balances for ethanol can be presented in many ways. The first is to compare the energy required to make the fuel compared to the energy produced. The two other ways could be considered to be full cycle energy balances, in these cases credits would be given for the improved energy efficiency when ethanol blends are consumed and for the energy savings in the refinery when ethanol's high octane rating is utilized. Another way of considering the energy balance would be to only include inputs derived from fossil fuels. Wang (1997) reports his data in this form. All four cases are presented here. The energy balances are shown in Table 5-2.

The total energy balance for lignocellulosic ethanol is not as favourable as that of corn ethanol. It is obvious from the table that the difference is totally within the ethanol plant. There are several reasons for this including the fact that one of the co-products is electricity and there is a loss of efficiency converting the thermal energy to electrical energy. The ethanol yields are not as high as for corn and it is reasonable to expect that more energy will be required to process the more difficult feedstocks. The plant also produces its own enzymes, which diverts a portion of the sugars produced from ethanol production. Enzyme consumption is higher than it is for a corn plant. The energy used in the ethanol plant is 99% from the biomass feedstock with 1% from diesel fuel. The energy balance comparing fossil fuels input to transportation fuels output is very favourable, substantially higher than corn ethanol and gasoline.

Unlike the greenhouse gas balances shown previously, the residue feedstocks, straw and stover, have the best energy balances for the cases analyzed. The benefits of carbon sequestration that switchgrass and hay enjoy do not impact the energy balances.

Table 5-2. Energy Balances for Year 2000, Gasoline and Ethanol.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered
Energy Inputs						
Feedstock recovery	116,900	100,200	40,900	44,900	14,900	50,800
Feedstock Transmission	4,600	12,100	36,100	32,500	34,000	36,700
Fuel production	106,000	595,900	1,251,000	1,034,000	995,800	1,293,300
Fuel Distribution, Storage and Dispensing	7,300	15,500	15,500	15,500	15,500	15,500
Fertilizer	0	97,800	79,100	79,000	179,100	62,200
Total Inputs	235,000	821,500	1,422,600	1,205,900	1,239,300	1,458,500
Co-product Credits	0	156,250[1]	136,100	114,725	117,155	137,000
Net Inputs	235,000	665,250	1,286,500	1,091,175	1,122,145	1,321,500
Net Inputs Fossil fuels	235,000	665,250	42,380	62,860	141,770	35,310
Energy Output	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
Effective Energy Output, 10% Blends*		1,141,600	1,141,600	1,141,600	1,141,600	1,141,600
Effective Energy Output, 85% Blends*		1,063,000	1,063,000	1,063,000	1,063,000	1,063,000
Net Energy	765,000	334,750	-286,500	-91,175	-122,145	-321,500
Net energy (output –fossil inputs)	765,000	334,750	957,620	937,140	858,230	964,690
Net effective Energy 10% Blends**		516,850	-144,900	50,425	19,455	-179,900
Net effective Energy 85% Blends**		397,750	-223,500	-28,175	-59,145	-258,500

* Based on the energy content of the blended gasoline, allowing for the better energy specific fuel consumption of ethanol. The additional effective energy for a 10% ethanol blend is: 0.01*(120,000 BTU/USgal/(84,750 BTU/USgal*0.10))=141,600 BTU/Million BTU delivered.

** Includes the refinery energy savings due to ethanol's octane value which equals 90% of 45,000 BTU/million BTU. 40,500 BTU/million BTU.

[1] Includes transportation energy to deliver DDGS to consumer.

5.1.3 Full Cycle Greenhouse Gas Emissions for 10% Ethanol Blends in 2000

The full cycle greenhouse gas emissions for 10% ethanol blends and gasoline are shown in Table 5-3. The assumptions are that the ethanol is used in the refinery to take advantage of the octane of the ethanol and that 10% ethanol blends achieve a 1% better energy specific fuel consumption. This is equivalent to a 2.5% volumetric fuel economy penalty. Results are presented on the basis of grams of CO_2 equivalent per mile drive.

Table 5-3. Full Cycle Emissions of Greenhouse Gases for Gasoline and 10% Ethanol Blends for Various Feedstocks in 2000.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile
Vehicle Operation	370.8	369.4	369.4	369.4	369.4	369.4
Fuel Dispensing	0.8	0.8	0.8	0.8	0.8	0.8
Fuel Storage and Distribution	4.0	4.2	4.2	4.2	4.2	4.2
Fuel production	44.7	53.4	41.9	42.2	42.3	42.4
Feedstock Transport	1.9	2.3	3.4	3.2	3.3	3.4
Feedstock and Fertilizer Production	42.0	44.1	42.5	42.6	43.6	42.5
Land Use Changes	0.0	0.3	-2.6	0.9	1.7	-1.7
Leaks and Flares	9.8	9.0	9.0	9.0	9.0	9.0
Emissions Displaced by Co-products	0.0	-4.5	-4.9	-4.0	-4.0	-4.9
Carbon in Fuel from CO_2 in Air	0.0	-23.9	-23.9	-23.9	-23.9	-23.9
Sub-total	474.0	454.4	439.9	444.5	446.3	441.2
Vehicle assembly and Transport	5.6	5.6	5.6	5.6	5.6	5.6
Materials in Vehicles	30.7	30.6	30.6	30.6	30.6	30.6
Total	510.3	490.6	476.1	480.7	482.5	477.4
% Change		-3.9	-6.7	-5.8	-5.4	-6.4

5.1.4 Full Cycle Greenhouse Gas Emissions for 85% Ethanol Blends in 2000

The greenhouse gas emission results for E85 made from the feedstocks of interest are shown in Table 5-4. The E85 has been assumed to provide 5% better energy specific fuel consumption based on actual experience with the vehicles.

Table 5-4. Full Cycle Greenhouse Gas Emissions for Gasoline and E85 for the Year 2000.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile
Vehicle Operation	370.8	340.4	340.4	340.4	340.4	340.4
Fuel Dispensing	0.8	0.8	0.8	0.8	0.8	0.8
Fuel Storage and Distribution	4.0	6.7	6.7	6.7	6.7	6.7
Fuel production	44.7	160.0	33.8	36.8	37.5	38.8
Feedstock Transport	1.9	6.5	18.6	16.8	17.5	18.9
Feedstock and Fertilizer Production	42.0	68.2	50.1	51.7	62.4	50.2
Land Use Changes	0.0	3.5	-27.9	9.8	18.1	-18.9
Leaks and Flares	9.8	1.9	1.9	1.9	1.9	1.9
Emissions Displaced by Co-products	0.0	-49.2	-53.1	-43.7	-44.1	-53.3
Carbon in Fuel from CO_2 in Air	0.0	-259.9	-259.9	-259.9	-259.9	-259.9
Sub-total	474.0	278.9	111.3	161.2	181.1	125.6
Vehicle assembly and Transport	5.6	5.6	5.6	5.6	5.6	5.6
Materials in Vehicles	30.7	30.8	30.8	30.8	30.8	30.8
Total	510.3	315.3	147.7	197.6	217.5	162.0
% Change		-38.2	-71.0	-61.3	-57.4	-68.3

5.1.5 Western Canada Wheat Straw

The composition of wheat straw in Western Canada appears to be significantly different from that of Ontario wheat straw. This requires less fertilizer to be used to replace the nutrients that the straw would normally provide. To determine the impact on greenhouse gas emissions both cases for wheat straw were modeled for the year 2000. The comparison for the ethanol production cycle is shown in Table 5-5 and for the full cycle in Table 5-6.

Table 5-5. Comparison of Production cycle for Ethanol between Ontario and Western Canada Wheat Straw.

	Gasoline	Ethanol	Ethanol
Feedstock	Crude oil	Ontario Wheat straw	Western Canada Wheat straw
Units	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer
Fuel Dispensing	160	165	165
Fuel Storage and Distribution	774	1,534	1,534
Fuel Production	8,755	7,439	7,439
Feedstock Transport	371	4,446	4,446
Feedstock Recovery	8,219	1,956	1,956
Land Use Changes	0	4,692	1,756
Fertilizer Manufacture	0	12,090	4,330
Leaks and Flares	1,821	0	0
Emissions Displaced by Co-products	0	-11,460	-11,460
Total	20,200	20,862	10,166

The reduced fertilizer requirements in Western Canada reduce greenhouse gas emissions for the production cycle by 51%.

Table 5-6. Full Cycle Emissions of Greenhouse Gases for Gasoline and 10% Ethanol Blends from Ontario and Western Canada Wheat Straw in 2000.

	Gasoline	Ethanol	Ethanol
Feedstock	Crude oil	Ontario Wheat straw	Western Canada Wheat straw
Units	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile
Vehicle Operation	370.8	369.4	369.4
Fuel Dispensing	0.8	0.8	0.8
Fuel Storage and Distribution	4.0	4.2	4.2
Fuel production	44.7	42.3	42.3
Feedstock Transport	1.9	3.3	3.3
Feedstock and Fertilizer Production	42.0	43.6	40.8
Land Use Changes	0.0	1.7	0.6
Leaks and Flares	9.8	9.0	9.0
Emissions Displaced by Co-products	0.0	-4.0	-4.0
Carbon in Fuel from CO_2 in Air	0.0	-23.9	-23.9
Sub-total	474.0	446.3	442.5
Vehicle assembly and Transport	5.6	5.6	5.6
Materials in Vehicles	30.7	30.6	30.6
Total	510.3	482.5	478.7
% Change		-5.4	-6.2

5.1.6 Summary for Year 2000

Ethanol produced from lignocellulosic feedstocks with current technology can produce significant reductions in greenhouse gas emissions compared to gasoline. The reductions are 40 to 70% higher than the reductions that corn ethanol currently produces. There are significant variations between different feedstocks created by the ability of some to sequester carbon and the ethanol yield that the different feedstocks provide.

5.2 Emissions and Energy Balances for Ethanol in 2010

For the year 2010 there will be a number of changes to gasoline and ethanol production and use that will impact on greenhouse gas emissions. These major ones are listed below:

- Vehicle fuel economy will improve from 9.6 L/100 km to 9.0 L100km,
- Gasoline will have a sulphur content of 30 ppm, reducing vehicle emissions of carbon monoxide, hydrocarbons and oxides of nitrogen,

- More fossil fuel will be used to produce electricity in Ontario.

These changes will reduce the greenhouse gas emissions for both gasoline and ethanol blends on a per mile driven basis.

5.2.1 Greenhouse Gas Emissions for the Ethanol Production Cycle in 2010

The greenhouse gas emissions for the year 2010 for ethanol production cycle where the ethanol is made from the feedstocks of interest is shown in Table 5-7. The gasoline and ethanol from corn cycles are shown for comparison.

Table 5-7. Greenhouse Gas Emissions for the Production Cycle of Crude Oil and Ethanol in 2010.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer	Grams CO_2 eq/million BTU delivered to consumer
Fuel Dispensing	162	196	196	196	196	196
Fuel Storage and Distribution	703	1,501	1,501	1,501	1,501	1,501
Fuel Production	10,448	31,320	5,737	6,518	6,701	7,007
Feedstock Transport	393	1,514	3,793	3,385	3,557	3,843
Feedstock Recovery	8,462	8,506	4,515	4,868	1,587	5,528
Land Use Changes	0	297	-5,975	1,757	3,684	-4,004
Fertilizer Manufacture	0	6,007	4,196	4,109	9,457	3,221
Leaks and Flares	1,772	0	0	0	0	0
Emissions Displaced by Co-products	0	-10,923	-10,405	-8,563	-8,681	-10,439
Total	21,940	38,420	3,560	13,771	18,003	6,854

The total greenhouse gas emissions from the lignocellulosic feedstocks have not changed dramatically. There has been a drop in emissions associated with ethanol production and farming but also a drop in co-product credits since more ethanol and less electricity is being made.

5.2.2 Energy Balances for the Ethanol Production Cycle in 2010

The energy balances for ethanol in 2010 is presented in Table 5-8 in the same format as for the year 2000. Energy balances have improved substantially compared to the year 2000 for the ethanol production cases.

Table 5-8. Energy Balances for Year 2010, Gasoline and Ethanol.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered	BTU/10^6 BTU Delivered
Energy Inputs						
Feedstock recovery	116,800	95,200	32,700	35,600	11,900	40,500
Feedstock Transmission	4,700	11,400	28,600	25,500	26,800	29,000
Fuel production	120,700	476,700	965,000	749,000	790,000	997,000
Fuel Distribution, Storage and Dispensing	7,100	15,100	15,100	15,100	15,100	15,100
Fertilizer	0	88,000	62,600	62,200	125,600	49,500
Total Inputs	249,300	686,400	1,104,000	887,400	969,400	1,131,000
Co-product Credits	0	136,890[2]	105,475	89,000	91,000	106,100
Net Inputs	249,300	549,510	998,525	798,400	878,400	1,025,000
Net Inputs Fossil fuels	249,300	549,510	39,700	54,190	93,460	34,380
Energy Output	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
Net energy (output –fossil inputs)	765,000	334,750	960,300	945,810	906,540	965,620
Effective Energy Output, 10% Blends*		1,141,600	1,141,600	1,141,600	1,141,600	1,141,600
Effective Energy Output, 85% Blends*		1,063,000	1,063,000	1,063,000	1,063,000	1,063,000
Net Energy	751,700	450,490	1,475	201,600	121,600	-25,000
Net effective Energy 10% Blends**		630,790	163,075	343,200	263,200	116,600
Net effective Energy 85% Blends**		513,490	64,475	264,600	184,600	38,000

* Based on the energy content of the blended gasoline, allowing for the better energy specific fuel consumption of ethanol. The additional effective energy for a 10% ethanol blend is: 0.01*(120,000 BTU/USgal/(84,750 BTU/USgal*0.10))=141,600 BTU/Million BTU delivered.

** Includes the refinery energy savings due to ethanol's octane value which equals 90% of 45,000 BTU/million BTU. 40,500 BTU/million BTU.

---

[2] Includes transportation energy to deliver DDGS to consumer.

The overall energy balances for the lignocellulosic feedstocks have improved significantly over the year 2000 due to the more effective fermentations and less electricity being produced. The higher yielding ethanol feedstocks have the best energy balances. All feedstocks produce a positive effective energy balance. There are only minor changes in the fossil fuel energy balances compared to the year 2000.

5.2.3 Full Cycle Greenhouse Gas Emissions for 10% Ethanol Blends in 2010

The full cycle greenhouse gas emissions are presented in Table 5-9. The same assumptions regarding fuel economy are made as in 2000. Greenhouse gas emissions are lower overall due to improved gasoline vehicle fuel economy.

Table 5-9. Full Cycle Emissions of Greenhouse Gases for Gasoline and 10% Ethanol Blends for Various Feedstocks in 2010.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile
Vehicle Operation	341.7	339.4	339.4	339.4	339.4	339.4
Fuel Dispensing	0.8	0.8	0.8	0.8	0.8	0.8
Fuel Storage and Distribution	3.4	3.6	3.6	3.6	3.6	3.6
Fuel production	50.1	55.0	46.5	46.8	46.9	47.0
Feedstock Transport	1.9	2.2	3.0	2.9	2.9	3.0
Feedstock and Fertilizer Production	40.5	42.1	40.2	40.2	40.9	40.2
Land Use Changes	0.0	0.1	-2.0	0.6	1.2	-1.3
Leaks and Flares	8.5	7.8	7.8	7.8	7.8	7.8
Emissions Displaced by Co-products	0.0	-3.6	-3.4	-2.8	-2.9	-3.5
Carbon in Fuel from CO_2 in Air	0.0	-22.4	-22.4	-22.4	-22.4	-22.4
Sub-total	446.7	425.0	413.4	416.8	418.2	414.5
Vehicle assembly and Transport	5.3	5.3	5.3	5.3	5.3	5.3
Materials in Vehicles	28.1	28.1	28.1	28.1	28.1	28.1
Total	480.1	458.4	446.7	450.1	451.5	447.8
% Change		-4.5	-6.9	-6.2	-5.9	-6.7

The percent reductions compared to gasoline have increased compared to the year 2000. The reductions are 30 to 53% greater than that provided by corn ethanol.

5.2.4 Full Cycle Greenhouse Gas Emissions for 85% Ethanol Blends in 2010

The greenhouse gas emissions for E85 for the year 2010 are shown in Table 5-10 along with those for gasoline and corn ethanol for comparison.

Table 5-10. Full Cycle Greenhouse Gas Emissions for Gasoline and E85 for the Year 2010.

	Gasoline	Ethanol	Ethanol	Ethanol	Ethanol	Ethanol
Feedstock	Crude oil	Corn	Switchgrass	Corn stover	Wheat straw	Hay
Units	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile	Grams CO_2 eq/mile
Vehicle Operation	341.7	312.8	312.8	312.8	312.8	312.8
Fuel Dispensing	0.8	0.9	0.9	0.9	0.9	0.9
Fuel Storage and Distribution	3.4	6.1	6.1	6.1	6.1	6.1
Fuel production	50.1	122.8	30.5	33.3	32.6	35.1
Feedstock Transport	1.9	5.8	14.1	12.6	13.2	14.2
Feedstock and Fertilizer Production	40.5	60.3	39.4	40.3	47.8	39.5
Land Use Changes	0.0	1.1	-21.6	6.3	13.3	-14.4
Leaks and Flares	8.5	1.7	1.7	1.7	1.7	1.7
Emissions Displaced by Co-products	0.0	-39.4	-37.5	-30.9	-31.3	-37.7
Carbon in Fuel from CO_2 in Air	0.0	-243.4	-243.4	-243.4	-243.4	-243.4
Sub-total	446.7	228.7	102.9	139.7	153.5	114.8
Vehicle assembly and Transport	5.3	5.3	5.3	5.3	5.3	5.3
Materials in Vehicles	28.1	28.2	28.2	28.2	28.2	28.2
Total	480.1	262.1	136.4	173.2	187.0	148.3
% Change		-45.4	-71.6	-63.9	-60.4	-69.1

There have been small increases in the relative reductions of greenhouse gases from lignocellulosic feedstocks compared in the year 2010 versus the year 2000.

5.2.5 Summary

Greenhouse gases from lignocellulosic ethanol decrease slightly faster than emissions from gasoline over the period 2000 to 2010. The emissions continue to be substantially lower than the emissions from gasoline whether the ethanol is used as 10% blend with gasoline or as an 85% ethanol fuel.

The full cycle emissions of Individual greenhouse gases in 2000 and 2010 for ethanol made from switchgrass and corn stover in a 10% blend and as E85 are compared to gasoline in Table 5-11. Notice the higher upstream emissions for methane and nitrous oxide due to the combustion of the lignin and the application of nitrogen fertilizers.

The model also calculates the full cycle emissions of non-greenhouse gases. The data for the same condition as in the Table 5-11 is presented in Table 5-12. The data is segregated by vehicle operation, upstream and vehicle material and assembly.

Table 5-11. Fuel Cycle Emissions of Individual Greenhouse Gases in 2000 and 2010

	2000					2010				
	Gasoline	10% Ethanol		E85		Gasoline	10% Ethanol		E85	
Units	gram/mile	gram/mile		gram/mile		gram/mile	gram/mile		gram/mile	
Feedstock	Crude Oil	Stover	Switchgrass	Stover	Switchgrass	Crude Oil	Stover	Switchgrass	Stover	Switchgrass
CO_2										
Vehicle Operation	344	343	343	315	315	330	328	328	302	302
Upstream	84	55	51	-234	-280	87	60	57	-214	-249
Veh Mat'l & Assembly	35	35	35	35	35	32	32	32	32	32
Total	463	433	428	116	70	449	420	417	120	85
% Total CO_2 Equiv.	90.8	90.0	89.9	58.6	47.3	93.7	93.3	93.3	69.0	62.5
CH_4										
Vehicle Operation	0.167	0.174	0.174	0.167	0.167	0.157	0.163	0.163	0.157	0.157
Upstream	0.823	0.855	0.854	1.140	1.138	0.737	0.754	0.754	0.896	0.904
Veh Mat'l & Assembly	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007	0.007
Total	0.999	1.037	1.036	1.315	1.314	0.901	0.924	0.925	1.060	1.068
% Total CO_2 Equiv.	4.1	4.5	4.6	14.0	18.6	3.9	4.3	4.4	12.9	16.5
N_20										
Vehicle Operation	0.062	0.062	0.062	0.062	0.062	0.019	0.019	0.019	0.019	0.019
Upstream	0.007	0.016	0.015	0.102	0.091	0.007	0.013	0.013	0.076	0.069
Veh Mat'l & Assembly	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Total	0.070	0.079	0.078	0.165	0.155	0.027	0.034	0.034	0.097	0.090
% Total CO_2 Equiv.	4.3	5.1	5.1	25.8	32.5	1.7	2.3	2.3	17.3	20.5
Total CO_2 Equiv.	510	481	476	198	148	480	450	447	173	136

Table 5-12. Fuel Cycle Emissions of Individual Non-Greenhouse Gases in 2000 and 2010

	2000					2010				
	Gasoline	10% Ethanol		E85		Gasoline	10% Ethanol		E85	
Units	gram/mile	gram/mile		gram/mile		gram/mile	gram/mile		gram/mile	
Feedstock	Crude Oil	Stover	Switchgrass	Stover	Switchgrass	Crude Oil	Stover	Switchgrass	Stover	Switchgrass
CO										
Vehicle Operation	10.888	9.043	9.043	10.888	10.888	6.255	5.195	5.195	6.255	6.255
Upstream	0.589	0.614	0.594	0.844	0.623	0.539	0.551	0.536	0.658	0.496
Veh Mat'l & Assembly	0.008	0.008	0.008	0.000	0.008	0.008	0.008	0.008	0.008	0.008
Total	11.485	9.665	9.645	11.741	11.519	6.801	5.754	5.739	6.921	6.758
NOx										
Vehicle Operation	1.107	1.098	1.098	1.107	1.107	0.605	0.601	0.601	0.605	0.605
Upstream	0.721	0.793	0.788	1.492	1.431	0.550	0.596	0.592	1.030	0.987
Veh Mat'l & Assembly	0.060	0.060	0.060	0.060	0.060	0.049	0.049	0.049	0.049	0.049
Total	1.887	1.951	1.946	2.659	2.598	1.205	1.246	1.242	1.685	1.642
VOC-ozone weighted										
Vehicle Operation	1.202	0.990	0.990	0.832	0.832	0.706	0.596	0.596	0.463	0.463
Upstream	0.406	0.392	0.391	0.241	0.231	0.259	0.251	0.250	0.158	0.151
Veh Mat'l & Assembly	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Total	1.610	1.384	1.383	1.076	1.066	0.968	0.849	0.848	0.623	0.616
SOx										
Vehicle Operation	0.099	0.076	0.076	0.042	0.042	0.093	0.031	0.031	0.040	0.040
Upstream	0.199	0.200	0.200	0.199	0.206	0.164	0.160	0.161	0.122	0.127
Veh Mat'l & Assembly	0.096	0.096	0.096	0.096	0.096	0.063	0.063	0.063	0.063	0.063
Total	0.394	0.371	0.372	0.337	0.344	0.320	0.254	0.254	0.225	0.230
Particulate Matter										
Vehicle Operation	0.049	0.047	0.047	0.049	0.049	0.046	0.044	0.044	0.046	0.046
Upstream	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Veh Mat'l & Assembly	0.011	0.011	0.011	0.011	0.011	0.006	0.006	0.006	0.006	0.006
Total	0.060	0.058	0.058	0.060	0.060	0.052	0.050	0.050	0.053	0.053

5.3 The Potential for Lignocellulosic Ethanol to Contribute to Meeting Canada's Commitment under the Kyoto Protocol

Lignocellulosic ethanol has great potential to reduce greenhouse gas emissions in Canada. A commercial scale plant producing 225 million litres per year will require 600,000 to 750,000 tonnes of feedstock per year, depending on the feedstock used. This is 20 to 25% of the corn stover harvestable in Ontario. There is also sufficient wheat straw available in areas of western Canada to supply several plants. Canada has 22 million hectares of unimproved farmlands a portion of which could be dedicated to energy crops such as switchgrass or hay. Within the 2000 to 2010 time period it is feasible to consider four or more commercial scale plants.

We will consider a scenario where the first plant will process corn stover, the next two wheat straw in western Canada and two more processing switchgrass. The ethanol will be used as a 10% blend with gasoline. The greenhouse gas emission reductions possible in the year 2010 from such a scenario are shown in Table 5-13.

Table 5-13. Summary of Predicated Results for 2010 Ethanol Production Scenario with a 10% Ethanol Blend.

Cumulative Volume ML/yr.	225	450	675	900	1125
Feedstock	Corn Stover	Wheat Straw	Wheat Straw	Switchgrass	Switchgrass
Total Feedstock Required kt/yr.	536,000	1,098,000	1,661,000	2,261,000	2,861,000
Predicated Fuel Cycle Emissions g/mile					
CO_2	420	420	419	419	419
CH_4	0.918	0.917	0.916	0.917	0.917
N_2O	0.034	0.033	0.033	0.033	0.033
Total CO_2 eq	450	450	449	448	448
Predicated CO_2 Reduction Relative to Gasoline	-6.2%	-6.3	-6.4	-6.5	-6.6
Gram CO_2 eq/mile	30.0	30.6	30.9	31.5	31.9
ktonnes	466	949	1,437	1,955	2,470

In December 1997, the parties to the 1992 United Nations Framework Convention on Climate Change (FCCC) adopted a protocol to the Convention (the Kyoto Protocol) to limit emissions of greenhouse gases. The Protocol will come into force when fifty-five countries covering a minimum of fifty-five percent of the FCCC Annex 1 countries emissions, have ratified the protocol. Canada is an Annex 1 country and has accepted a GHG reduction target of six percent below its 1990 level of 564 Mt CO_2 equivalent by the end of the first reporting period, 2008-2012.

Analysis conducted by Environment Canada indicates that Canada's net GHG emissions need to be reduced by 21-26 percent, or approximately 140 to 185 million tonnes, below the level projected to occur in 2010 under a business-as-usual scenario to achieve the six percent reduction target. This is a very difficult challenge for Canada given its growing population, cold climate, long transportation distances, and the fact that our exported raw materials contain significant embedded fossil fuel emissions.

Emissions of greenhouse gases from Canadian road transportation sources in 1995 totalled approximately 123 Mt (Jaques et al, 1997). This amounts to about 19.9% of the total CO_2 equivalent greenhouse gas emissions from energy and non-energy sources in 1995 (23.8% if considering only energy sources) and about 74.3% of the total greenhouse gas emissions from the Transportation Sector. The greenhouse emissions from the road transportation sector arise 51.1% from automobiles, 26.0% from heavy-duty trucks and buses and 22.8% from light-duty trucks, with the remainder being from motorcycles.

Ethanol produced from lignocellulosics and blended with gasoline will reduced emissions of greenhouse gases. If ethanol production can be expanded to 1.125 billion litres per year by 2010 then emissions of GHG can be reduced by 2.47 million tonnes annually. This represents 1.3 to 1.8% of the total reduction required to meet Canada's commitment to the Kyoto Protocol. It also represents 9.4 to 13.5% of agriculture's share of the required reduction or 5 to 7% of the transportation sector's share.

6. Sensitivity Analyses, Data Gaps and Uncertainties

6.1 Sensitivity Analyses

The choice of feedstocks chosen for the modeling was designed to provide insight into the sensitivity of the full cycle to some of the variables. The variables that were considered for sensitivity analyses include;

- Land use
- Biomass yield
- Fertilizer applied
- Ethanol plant yield
- Plant energy use
- Co-product volumes

The issue of the impact of land use is addressed by comparing the greenhouse gas emissions of the two energy crops, switchgrass and hay, against the crop residues that have been assumed to have no impact on carbon sequestration in the soil or in the annual biomass. The average difference between these two options is about 13,700 gms CO_2/million BTU of fuel produced. This is about 15% of the full cycle emissions for gasoline and is the single largest factor in accounting for the differences between the feedstocks. These energy crops have lower ethanol yields and it is likely that ethanol plants designed to process residues could be smaller and less expensive because they can produce more ethanol from a given mass of feedstock. The lowest cost ethanol may not be from the feedstock that provides the largest greenhouse gas emissions reductions.

Biomass yield has a relatively small impact on total greenhouse gas emissions. It does impact the amount of carbon that can be sequestered in the plant biomass and thus has an impact on land use. Switchgrass with its higher yield has the ability to sequester more carbon than hay. The difference is small, about 2-3% of the emissions from the full gasoline cycle. Yield does not impact the residues except if it impacts on the energy required for baling. There is not enough good information available on the energy consumption in this area to determine the magnitude of this impact.

The comparison of wheat straw grown in Ontario and Western Canadian wheat straw is really the difference in fertilizer required. Wheat yields in Ontario are much higher than in Western Canada. These higher yields require more nitrogen fertilizer be applied and part of this fertilizer ends up in the straw. The Ontario case modeled has three times the fertilizer applied as the Western Canada case. The difference in greenhouse gas emissions between the two cases is 10,600 gms/million BTU, about 12% of the gasoline full cycle emissions. If more fertilizer was applied to one of the energy crops then some of the increase in emissions from the fertilizer will be offset by the increase in plant biomass growth and carbon sequestration. It is beyond the scope of this study to determine the magnitude of this offsetting impact.

The comparison of each feedstock between 2000 and 2010 is a comparison of plant yield. In each case the ethanol production increases with time as organisms are developed that have the capability of converting pentose sugars to ethanol. Offsetting this ethanol yield is a decrease in the amount of electricity produced as a co-product. There is very little differences in the greenhouse gas emissions for each feedstock in the two years. Some have a small increase and some show a small decrease. We don't think that the energy consumption data for the ethanol plant and the electricity available for sale over time is rigorous enough at this stage for these small differences to be considered significant. The energy consumption for any process improves over time as small improvements are made in the

process. In a process such as enzymatic hydrolysis where small changes in viscosity could impact significantly the pumping energy required it is very difficult to predict the future energy requirements and thus the quantity of co-products available and the actual impact on greenhouse gas emissions. The increasing yield does appear to significantly improve the energy balance of the process.

The impact of the electricity on greenhouse gas emissions is about three times that of the acetic acid. The impact on the energy balance is about equal due to the efficiency of electricity generation. Since the electricity available for sale is only a small part of the energy produced by the lignin the biggest impact on co-products is probably the consumption of steam and electricity in the process. A 10% reduction in electricity use in the plant is likely to increase the electricity available for sale by 20%.

6.2 Data Gaps and Uncertainties

Some of the systems considered in this analyses such as the full scale production of ethanol from lignocellulosics and the production of switchgrass as an energy crop have not been demonstrated on a commercial scale. The data used for this analyses has been developed from pilot scale operations and in some cases, such as electricity generation from lignin, has had engineering judgement applied to calculate the required modeling inputs.

The agronomic data for corn stover, wheat straw and hay is relatively certain. The data for switchgrass has been compiled and compared with multiple sources. It is reasonable data for the Ontario region. Switchgrass yields in western Canada will be less than modeled here. That will not effect the greenhouse gas emissions but will impact on the potential size of the resource.

Changes in soil carbon projected for switchgrass and hay are based on estimates taken from the Sinks Table Foundation report and not on experience in Canada. Some US researchers have measured increases in soil carbon with the cultivation of switchgrass (Tolbert, 1999) so we are relatively comfortable with the data used.

The data used for modeling the ethanol plant is the most difficult to compare with other sources. Iogen are the world leaders with respect to enzymatic hydrolysis. Other sources of data that could be used for comparison have been published by universities and government research institutions in the US. That data is not likely to be as definitive as Iogen's data.

The results for the year 2010 are based on complete conversion of pentose sugars to ethanol. This process has been demonstrated in the laboratories of several researchers but not in demonstration plants that deal with real world hydrolyzates. There are a number of researchers working on this problem in Canada, the United States and other countries around the world. The researchers are following a number of different scientific paths and it is reasonable to assume that a commercially viable solution will be found before the year 2010. In any case the conversion of the pentose sugars to electricity while not economically attractive has little impact on greenhouse gas emissions if the displaced electricity is being produced from natural gas.

The area of greatest uncertainty within the Iogen process, as modeled, is around the energy balance in the plant. The requirements for steam and electricity within the process can be difficult to predict based on laboratory scale-up data. The surplus electricity for sale therefore has a high degree of uncertainty, particularly projecting out ten years. Plant throughputs and efficiencies always improve as operators become more familiar and develop a better understanding of the process. It is highly likely that over time a lignocellulosic plant will become more efficient and have more electricity available for sale than Iogen are currently projecting. The results projected for 2010 may therefore be pessimistic.

7. Conclusions

Ethanol produced from lignocellulosic feedstocks in Ontario and incorporated at the 10% level into a refinery blending system is capable of reducing greenhouse gas emissions by 5.4 to 6.7% depending on the feedstock compared to conventional gasoline. This is using existing farming and refining practices, and assuming that the ethanol production technology being developed by Iogen can be put into commercial practice. It is based on ethanol yields that have been demonstrated in the laboratory. By the year 2010 the ethanol production technology is expected to improve, increasing the ethanol produced from any feedstock but this will be offset, but reduced production of electricity. The greenhouse gas emissions reduction in 2010 is projected to be from 5.9 to 6.9% based on the following assumptions:

- Low sulphur gasoline will be produced which requires more energy to produce,
- Ethanol plant energy use will not change significantly,
- There will be a continuing improvement in energy efficiency in gasoline refining and farming practices,
- Crop yields will continue to improve as will the inputs required to grow them at the same rate as historical changes.

If the industry is expanded to produce 1.125 billion litres of ethanol per year by 2010 the total GHG reductions will be 2.47 million tonnes of CO_2 equivalents annually.

These values are dependent on the use of ethanol in such a manner that its high-octane properties can be fully utilized. The recent changes in the allowable gasoline sulphur content may put an octane strain on most Ontario refineries. The extent of the octane shortage will be a function of the technology that refiners use to remove the sulphur. The use of 10% ethanol should be enough to eliminate that octane shortage caused by the de-sulphurization of the gasoline in most refineries. The use of ethanol would reduce the capital that refiners would otherwise have to invest in new octane generating capacity. There will be a limited window of opportunity to take advantage of this situation. Refiners will soon be committing to significant capital expenditures to remove sulphur.

The greenhouse gas reductions for E85 range from 57.4% to 71.0% in 2000. For the year 2010 the range in reduction is 60.4% to 71.8%

Ethanol production in Ontario in the year 2010 has a positive energy balance. The energy balance for producing ethanol from lignocellulosics is not as good as for producing ethanol from corn. The feedstock is more difficult to process and requires much more energy than does processing corn. This energy is supplied almost entirely from the lignin in the feedstock and thus the energy balance between fossil fuels used and transportation fuels produced is very favourable. The production of electricity and the inefficiencies of that production process make the comparisons of energy balances between processes difficult to compare.

Similar studies have been performed by other authors for ethanol production from lignocellulosics in the United States. Sheehan (1998) reports reductions greenhouse gas reductions of 72 to 117% for cellulosic ethanol from a number of studies performed from 1991 to 1997. There is very little detail on the assumptions for the various cases reviewed. Wang (1998) reported on a number of cases that are similar to those calculated here, including near and future time frames, herbaceous crops, and E10 and E85. In Table 7-1 a comparison of Wang's result with those generated here for switchgrass is given.

Recent work by Delucchi (EEA 1999) reported on cases with agricultural residues for a near term 1995 scenario and a 2015 switchgrass feedstock. In both cases the E10 and E85 was compared to reformulated gasoline. That data is also summarized in Table 7-1.

Table 7-1. Comparison of Results with those Reported by Wang and Delucchi.

Fuel	% Reduction Compared to Gasoline	
	Near Term Case	Future Case
E10 Wang	5.7	7.6
E10 Delucchi	4.4	7.6
E10 This Report	6.7	6.9
E85 Wang	67.6	67.5
E85 Delucchi	47.8	87.1
E85 This Report	71.0	71.6

The results are quite close for the two cases reported. The E10 case modeled here includes the higher engine efficiency and the refinery benefits that are not considered by Wang and Delucchi. That probably accounts for our higher near term E10 reduction. Delucchi's assumptions are not clear in his near term case so it is not possible to offer an explanation for the difference.

Wang does not model the land use changes as rigorously as Delucchi but rather quotes some of Delucchi's results and inputs those into his model. We could not find data to support all of the inputs used by Delucchi in calculating land use changes. We believe that the original Delucchi model overestimates the potential for soil carbon sequestration for grasses and underestimates the impact on biomass carbon sequestration. We have corrected the inputs for our calculations. This would account for the high value reported by Delucchi for the E85 future case.

Both Wang and Delucchi have significantly higher reductions for the future cases than the current case. The data received from logen does not support the magnitude of the improvement forecast by Wang and Delucchi.

To compare the results reported here to the % reductions for ethanol that were reported by Sheehan it is necessary to correct for the relative energy content of the ethanol and not correct by volume. A 10% ethanol blend has 6.7% of its energy content supplied by the ethanol. The switchgrass near term case therefore represents a 100% (6.7/6.7) reduction in greenhouse gas emissions compared to gasoline. The E85 has 78.5% of its energy from the ethanol and thus it could be reported that for E85 ethanol represents a 90% (71.0/78.5) reduction in greenhouse gas emissions. The difference between E10 and E85 is caused by the relative efficiencies of the fuels in the combustion process. For all of the feedstocks considered for the year 2000 and the E10 blends the range in reductions in greenhouse gas emission for ethanol relative to gasoline is 80 to 100%. For E85 the range is 73 to 90%. For the year 2010 the range for E10 is 88 to 103% and for E85 it is 77 to 91%.

8. References

(S&T)[2] Consultants Inc. 1999. An Assessment of Emissions from Ethanol-Gasoline Blends. Prepared for Environment Canada.

Agriculture and Agri-Food Canada, Research Branch. 1997. Agroecosystem Greenhouse Gas Balance Indicator: Methane Component. Report No. 21.

Agriculture and Agri-Food Canada, Research Branch. 1999. The Health of Our Air, Toward Sustainable Agriculture in Canada.

Agriculture and Agri-Food Canada. 1999b. Canadian Economic and Emissions Model for Agriculture. Report 1: Model Description.

Alberta Agriculture. 1999. Estimating the Value of Crop Residues. www.agric.gov.ab.ca/agdex/500/5-9-25.html .

Bransby, D. Switchgrass Profile. www.esd.ornl.gov/bfdp/papers/misc/switchgrass-profile.html.

Blunk, S.L., Jenkins, B.M., Kadam, K.L. 1999. Combustion Properties of Lignin Residue from Lignocellulosic Fermentation. Proceedings of the Fourth Biomass Conference of the Americas. August 29 – September 2, 1999. Oakland California.

Canadian Association of Petroleum Producers. September 1998. Oil and Natural Gas Industry Foundation Paper. Prepared for the National Climate Change Secretariat.

Coxworth, E., Campbell, CA. 1999. Industrial Materials Made From Agricultural Biomass. Agriculture and Agri-Food Canada Contract No. 01304-8-C091/007/SQ. A report prepared for the Agriculture and Agri-Food table on Climate Change.

Delucchi, M. 1998. Lifecycle Energy Use, Greenhouse-Gas Emissions, and Air Pollution from the Use of Transportation Fuels and Electricity. Institute of Transportation studies. University of California. Davis.

Delucchi, M. and Lipman, T., 1997. "Emissions of Non-CO_2 Greenhouse Gases from the Production and Use of Transportation Fuels and Electricity", Institute of Transportation Studies, University of California, at Davis, UCD-ITS-RR-97-5, February

Delucchi, M.A. 1993. "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity", Volume 2: Appendixes A-S, Argonne National Laboratory, Argonne, IL, U.S. Department of Commerce, NTIS.

Delucchi, M.A., 1991. "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity" Volume 1: main text, Argonne National Laboratory, Argonne, IL, U.S. Department of Commerce, NTIS, Nov.

Energy and Environment Analysis, Inc., 1999. "Fuel Supply Database Documentation, Fuel Strategy Database Development Project" prepared for US Department of Energy, Washington, DC", Revised Report, February, 1999.

Girouard, P., Zan, C., Mehdi, B., Samson, R. 1999. Economics and Carbon offset Potential of Biomass Fuels. Final Report 1999. PERD Contract 23341-6-2010/00 1/SQ.

Glassner, D.A., Hettenhaus, J.R., Schechinger,T.M. 1998. Corn Stover Collection Project. Bioenergy 1998.

Hochhauser, A.M., Benson, J.D., Burns, V.R., Gorse, R.A., Koehl, W.J., Painter, L.J., Reuter, R.M., Rutherford, J.A. 1993. Fuel Composition Effects on Automotive Fuel Economy – Auto/Oil Air Quality Improvement Research Program. SAE 930138.

Hunter, C., McGee, B. 1999. Survey of Pesticide Use in Ontario, 1998. Ontario Ministry of Agriculture, Food and Rural Affairs. Guelph, Ontario. ISBN 0-7743-9959-7.

Jaques, A, Neitzert, F. and Boileau, P., 1997, "Trends in Canada's Greenhouse Gas Emissions (1990-1995), Environment Canada Report En49-5/5-8E, ISBN 0-662-25643-3, April.

Jefferson, P.G., McCaughey, P., May, K., Darroch, B., Wright, S., Pahl, M., McFarlane, L., Wank, B. 1997. Biomass Productivity Evaluation of Native Grass Species in the Agro-Ecological Regions of the Prairie Provinces. Proceedings of the 1997 Ethanol Research and Development Workshop. Ottawa, Ontario. March 16-18, 1997.

Levelton Engineering Ltd. 1999. Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario. Prepared for Agriculture and Agri-Food Canada.

Levelton Engineering Ltd. 1999b. Alternative and Future Fuels and Energy Sources for Road Vehicles. Prepared for Transportation Issue Table. National Climate Change Process.

Lindley, J.A., Backer, L.F. 1994. Agricultural Residue Harvest and Collection. Prepared for Western Region Biomass Energy Program. PO#AA-PO-111671-12134.

Manitoba Rural Adaptation Council Inc. and the Canadian Wheat Board. 1999. The Market Competitiveness of Western Canadian Wheat. January 1999.

McElroy, A.R. 1997. Evaluation of Forages for Biomass Production in Ontario. Proceedings of the 1997 Ethanol Research and Development Workshop. Ottawa, Ontario. March 16-18, 1997.

National Sinks Table. 1998. National Sinks Table Foundation Paper. National Climate Change Process.

Natural Resources Canada. 1997. Canada's Energy Outlook 1996-2020.

Nyboer, J., Oliver, J. 1998. A Review of Energy Consumption in Canadian Oil Refineries and Upgraders 1990, 1994 to 1997. Simon Fraser University.

Office of Industrial Technology. US Department of Energy. E3 Handbook, Appendix B. www.oit.doe.gov/E3handbook/appenb.shtml .

OMAFRA. 1999. Hay – Area, Production, Yield and Price, Ontario, 1981-1996. www.gov.on.ca/OMAFRA/english/stats/crops/hay.html .

OMAFRA. 1999b. Estimated Area, Production and Farm Value of Specified Field Crops, Ontario, 1997, 1998, 1999. www.gov.on.ca/OMAFRA/english/stats/crops/estimate.html .

OMAFRA. 1999c. Straw for Sale – What is it Worth. www.gov.on.ca/OMAFRA/english/offices/duffs/common/press%20release/strawsal.html .

Purvin & Gertz, Inc. 1999. Petroleum Downstream Sector Industry Foundation Paper. Prepared for CPPI and presented to Climate Change Issue Table.

Ragazzi, R., Nelson, K. 1999. The Impact of a 10% Ethanol Blended Fuel on the Exhaust Emissions of Tier 0 and Tier 1 Light Duty Gasoline Vehicles at 35F. Colorado Department of Public Health and Environment. March 26,1999.

Reicosky, D.C. 1998. Soil Organic Matter after 30 Years of Silage Removal from Continuous Corn and Moldboard Plowing. USDA ARS, Morris, MN.

Tolbert, V.R., Joslin,J.D., Thorton, F.C., Bock, B.R., Pettry, D.E., Bandaranayake, W., Tyler, D., Houston, A., Schoenholtz, S. 1999. Biomass Crop Production: Benefits for Soil quality and Carbon Sequestration. Proceedings of the Fourth Biomass Conference of the Americas. Oakland, California. August 29 – September 2 1999.

Sheehan,J. 1998. The Role of Bioethanol in Global Climate Change. 1998 National Conference on Ethanol Policy and Marketing. Feb. 1998. Albuquerque, New Mexico.

Stumborg, M.A., Townley-Smith, I., Coxworth, E. 1995. Sustainability and Economic Issues for Cereal Crop Residue Export.

Stumborg, M.A., Mcleod, J.G., Jefferson, P.G., Timbers, G.E., Dubuc, J-P., Michaud, R., Samson, R. 1998. The Potential Production of Agricultural Biomass for Fuel Ethanol in Canada. Renewable Energy Technologies in Cold Climates '98. Montreal, Canada.

United Nations Framework Convention on Climate Change. Emissions Summary for Canada. www.unfccc.de/index.html .

US EPA. 1998. EPA Staff Paper on Gasoline Sulfur Issues. US EPA Office of Mobile Sources. EPA420-R-98-005.

US EPA. 1998b. Emissions of Nitrous Oxide from Highway Mobile Sources. EPA420-R-98-009.

Walsh, M.E., Becker,D. 1996. BIOCOST: A Software Program to Estimate the Cost of Producing Bioenergy Crops. Proceedings Bioenergy 1996. Nashville Tennessee. September 1996.

Wang, M., Saricks, C., Santini, D. 1999. Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions. ANL/ESD-38. Argonne National Laboratory.

Wang, M.Q., August 1999 "Transportation Fuel Cycles Model: Methodology, Development, Use, and Results", Greet 1.5, prepared by the Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Argonne, IL. ANL/ESD-39. Vol. 1 and Vol. 2.

Wang, M.Q., June 1996 "Transportation Fuel Cycles Model: Methodology and Use", Greet 1.0, prepared by the Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Argonne, IL.

Appendix A
Supporting Data for Fuel Cycle Analysis

LIGHT-DUTY VEHICLE EMISSIONS (gasoline and E10)					
Pollutant	Conventional gasoline				E10 Emissions RELATIVE to conventional gasoline
	Year 2000	Deterioration rate	Zero-mile, MY 1993	g/mi in base year	
	G/mi	g/mi/10000-mi	% change per MY year		
Fuel evaporation or leakage	0.37	0.02	-1.7	0.26	1
NMOC exhaust	0.92	0.0509	-5.5	0.84	0.91
CH4 exhaust	0.17	0.015	-3.5	0.08	1
CO exhaust	10.89	0.6829	-6	9.42	0.9
N2O exhaust	0.062	0	-3.5	0.08	1
NOx as NO2 exhaust	1.11	0.0281	-5	1.3	1
PM exhaust	0.05	0.005	-5	0.02	1
Consumption of lube oil*	1.64	n.a.	n.a.	1.64	1

Fuel Characteristics Used in the Fuel Cycle Model

FUEL	Higher heating values	Units	Value	Units	Density Value	Units	Carbon fraction	Sulphur fraction
Crude oil input to refineries (Year 2010)	0.1381	mmBTU/gal	5.800	mmBTU/bbl	3338	g/gal	0.850	0.01337
Residual fuel oil	0.1497	mmBTU/gal	6.287	mmBTU/bbl	3575	g/gal	0.858	0.00992
Diesel fuel	0.1387	mmBTU/gal	5.825	mmBTU/bbl	3192	g/gal	0.858	see above
F-T diesel from NG	0.1310	mmBTU/gal	22,260	g/mmBTU	2916	g/gal	0.848	0.00001
Canola diesel (was Soydiesel)	0.1325	mmBTU/gal	25,251	g/mmBTU	3346	g/gal	0.770	0.00008
DME (density, LHV from SAE paper 971607, HHV calced)	0.0751	mmBTU/gal	33,307	g/mmBTU	2501	g/gal	0.522	0.00001
Petrol diesel, biodiesel, and F-T diesel mix	0.1375	mmBTU/gal	23,446	g/mmBTU	3223	g/gal	0.840	0.00025
Petroleum coke	0.1434	mmBTU/gal	6.024	mmBTU/bbl	4321	g/gal	0.900	0.00800
Conventional gasoline	0.1251	mmBTU/gal	5.253	mmBTU/bbl	2791	g/gal	0.866	0.00032
Reformulated gasoline	0.1251	mmBTU/gal	5.253	mmBTU/bbl	2791	g/gal	0.866	0.00003
Reformulated gasoline: petroleum component only					2791	g/gal		
Gasoline used in tractors and engines	0.1251	mmBTU/gal	5.253	mmBTU/bbl	2791	g/gal	0.866	0.00003
Methanol	0.0645	mmBTU/gal	46,446	g/mmBTU	2996	g/gal	0.375	0.00001
Methanol/gasoline mix	0.0736	mmBTU/gal	40,294	g/mmBTU	2965	g/gal	0.444	0.00001
Ethanol	0.0846	mmBTU/gal	35,319	g/mmBTU	2988	g/gal	0.522	0.00001
Ethanol/gasoline mix	0.0907	mmBTU/gal	32,629	g/mmBTU	2958	g/gal	0.570	0.00001
Generic industrial coal	21.032	mmBTU/ton	10,516	BTU/lb.			0.598	0.00904
Utility coal	19.703	mmBTU/ton	9,851	BTU/lb.			0.562	0.00904
Coal to Methanol	19.703	mmBTU/ton	9,851	BTU/lb.			0.562	0.00904
Hydrogen	7470	g/mmBTU	338	BTU/SCF				
Refinery-made LPG	0.0920	mmBTU/gal	3.863	mmBTU/bbl	2053	g/gal		0.00001
LPG assumed in this analysis	0.0914	mmBTU/gal	3.838	mmBTU/bbl	1917	g/gal		0.00001
Electricity			3412	BTU/kWh				
Steam			1.200	mBTU/lb.				
Petroleum products produced in U. S. (generic)			5.395	mmBTU/bbl	0.1497	ton/bbl		
Other refinery oil			5.825	mmBTU/bbl				
Lube oil	0.1444	mmBTU/gal	6.065	mmBTU/bbl	3401	g/gal	0.858	0.00992
Wood	16.7	mmBTU/dt	8350	BTU/dry-lb.			0.520	0.00090
Grass	15.0	mmBTU/dt	7500	BTU/dry-lb.			0.484	0.00090
Butanes	0.103	mmBTU/gal						
Isobutylene	0.090	mmBTU/gal						

Appendix B

Gasoline Production Chapter

From

Corn Ethanol Study

B. Gasoline Production and Effects of Ethanol Blending

B.1 Gasoline Production and Supply in Southern Ontario

The Ontario petroleum refining industry has gone through dramatic changes over the past 25 years. Today, the production facilities consist of five refineries producing transportation fuels with some additional crude processing capability at Novacor in Sarnia, which produces chemicals. Total crude processing capacity in Ontario is approximately 500,000 barrels per calendar day. At present the industry is operating at about 90% crude capacity, however, in most cases secondary units are being run full.

Feedstock for Ontario refineries has traditionally come from Western Canadian crude oils, synthetics and bitumens. Some capability exists to import crude from the USA through Chicago based pipelining networks, but this has not generally proven economically feasible. Normally crude movements have been into the United States along with surplus propane, butanes and condensates. Starting in May 1999 the Sarnia-Montreal IPL pipeline has been reversed, opening up the import capabilities of offshore crude from world producers.

During the past 25 years, world crude oil crises have resulted in most major US refiners investing heavily in metallurgy and hardware to allow the processing of cheaper, heavier and sour crude oils. This has not been the case in Canada and in particular in Ontario. With the exception of Imperial Oil at Sarnia, Ontario refineries are still dependent mainly on light sweet crude oil. This dependency will increase as regulations for lower sulphur in gasoline and diesel fuels come into effect.

Although the Ontario refineries may be considered rather small and dependent on sweet crude oils, the petroleum refining industry has kept up to date with advanced computer control technology as well as modernization of their facilities. As a result, the industry is among the most efficient in the world and possesses excellent skills for optimizing feedstocks, blending components and quality requirements. Furthermore, the industry has an excellent distribution system throughout the province that consists of modern "state-of-the-art" pipeline networks linking all major centres within the golden horseshoe corridor from Sarnia to Montreal including a lateral to serve Ottawa. Along with modern product loading facilities and fuel efficient truck fleets, the distribution of products in Ontario is as efficient as any in the world.

The marketing of gasoline in Ontario has also undergone a major metamorphosis in recent years. Gone are thousands of small and often less efficient service stations. Today the emphasis is on large major service stations that offer many additional customer services like car washes, quick food outlets and basic corner-store items. In most cases these facilities are company owned and operated.

For this review, only the five complete refineries will be considered and a more in-depth discussion follows this brief overview. While information is provided on each refinery an aggregate of the data has been prepared to represent the Ontario refining industry. Modeling in this study has been done with the aggregate data that is representative of the Ontario industry, but does not apply to any specific refinery or company.

B.2 Description of Refineries, their Current Configuration and Effects of Fuel Sulphur Regulations

B.2.1 Petro-Canada, Oakville

The Petro-Canada Refinery in Oakville has a rated capacity of 85,000 barrels per stream day. The effective capacity used in this review is 80,500 barrels per calendar day. The original plant, built in 1958 was expanded in 1974 by mirror-imaging the Atmospheric Crude Unit, Fluid Catalytic Cracking Unit (FCCU) and Catalytic Reforming Unit along with necessary auxiliaries. Presently, the plant processes crude through parallel crude trains. The older crude unit operates basically on heavy sour asphaltic crude oils to meet a high asphalt demand. The newer crude unit processes light sweet crude to produce the usual components as well as lube oil feedstocks for the Petro-Canada Mississauga Lube Oil facility. The Mississauga Refinery is partially integrated with the Oakville Refinery. Besides producing at least part of Mississauga lube feedstock requirement, naphtha from Oakville is also moved to the Mississauga facility for reforming through their 10,000 bbls./d. Catalytic Reforming Unit.

The Oakville Refinery is a basic plant with small duplicated units however it has a reputation for excellent maintenance and high efficiency on-stream times. The refinery is presently engaged in construction and start-up of an Isomerization Unit that should increase gasoline pool R+M/2 octane capability.

B.2.2 Imperial Oil, Sarnia

This is Ontario's largest refinery rated at 126,000 barrels per stream day with an effective rating of 119,000 barrels per calendar day. The refinery is a highly complex plant that has a substantial gas-oil cracking capacity (47%), and is the only refinery in Ontario that has true bottoms upgrading capabilities. The refinery's Fluid Coking unit is a thermal cracking process utilizing fluidized-solids technique to remove carbon (coke) from continuous conversion of heavy, low-grade oils into lighter products. The refinery burns the coke produced as fuel. Over the years, a residuum-based stream from Imperial Oil's Strathcona, Alberta refinery has been processed here. Thus Imperial's Sarnia is equipped with an effective triad of FCCU, Hydrocracking Unit (HCU) and Coker, making it Ontario's lowest cost producer. As well, over past years Imperial has invested time and money at Sarnia to make the refinery one of North America's most energy efficient facilities, thus adding further to its cost competitiveness.

The refinery has both lube and aromatic facilities and has been integrated with Imperial Oil's Nanticoke refinery to optimize operations at both plants. With ample reforming, catalytic cracking and alkylate capacity within the integrated complex, Imperial should have no difficulty meeting new gasoline specifications other than sulphur in both gasoline and diesels.

B.2.3 Imperial Oil, Nanticoke

The Nanticoke Refinery was built in 1978 by Texaco and is Ontario's newest refinery. The refinery has an effective capacity of 112,000 barrels per calendar day. Originally designed as a major gasoline producer, the plant was upgraded in the late 1980's and early 1990's. Today it is an efficient fuels refinery with an improved FCCU, a continuous regenerating reformer and modern computerized operation and control.

Nevertheless, Nanticoke is still a basic fuels refinery that by and large is limited to sweet light crude although some light sour can also be processed now that the refinery has distillate

desulphurizing capabilities. As well, integration with Imperial Oil's Sarnia refinery should provide opportunities to alleviate some constraints on the refinery.

Although Nanticoke has excellent octane generating capability the plant may face problems with future gasoline sulphur specifications.

B.2.4 Shell Canada, Corunna

The Shell refinery at Corunna is rated at 80,400 barrels per stream day with an effective rating of 71,400 per calendar day. The plant processes light sweet and sour crude oil with occasional small amounts of heavy sour crude.

The refinery was originally build in 1952 and has been upgraded on a number of occasions. It has both a FCCU and a HCU as well as a small Viscbreaker. It produces aromatics in support of an associated petrochemical complex. The plant is limited on sulphur removal and will experience problems meeting future octane requirements.

B.2.5 Sunoco, Sarnia

The Sunoco Refinery at Sarnia is rated 85,000 barrels per stream day, but in this review it is given an effective rating of 70,000 barrels per calendar day. The Refinery has been updated and modernized and possesses "leading-edge" computerized control technology with on-line optimization of yield and energy value applications making it a very efficient and profit oriented operation. The refinery possesses the highest gas-oil cracking percentage (64%) in the province as well as ample octane capabilities with a large reformer and an adequate hydrofluoric acid Alkylation Unit. Although the effective capacity appears low compared to rated capacity, the refinery strives to operate all secondary units at capacity by processing mainly synthetic crude (no bottoms) and by purchases of feedstocks from other Sarnia chemical operations.

The refinery has BTX (benzene, toluene, xylene) facilities and produces aromatics, both for domestic and export markets. Like all Ontario refineries, Sunoco receives crude oil by pipeline and ships most of their products through their jointly owned pipeline network to London and Toronto terminals for distribution to their Ontario markets. Like all five Ontario refineries, Sunoco is accessible to the Great Lakes and the St. Lawrence Seaway System through their own dock and product loading facilities.

Sunoco is the only Ontario refiner who is presently blending 6-8% by volume of ethanol into their gasoline pool. They purchase all of CAI's fuel ethanol production from Chatham Ontario. The ethanol is blended into gasoline at Sunoco terminals in London, Toronto, and Sarnia.

Sunoco has ample octane and would have no problem meeting new gasoline specifications even without ethanol. Sunoco currently has the lowest gasoline sulphur level in the province. They will require upgrading to meet the 30 ppm sulphur gasoline standard in 2005.

B.2.6 Fuel Sulphur Regulations

The Federal Government has introduced new lower limits on sulphur in gasoline. The regulations will be phased in between 2002 and 2005. By 2005 the average sulphur content of gasoline must be less than 30 ppm. This is a significant reduction from the current Ontario average of about 500 ppm. Refiners have a number of processing options available to them to meet the new standards. All of the options require extra energy to be expended in the refinery. The energy is used to remove the sulphur from the refinery streams and to replace some gasoline octane that is lost in the sulphur removal process.

The CPPI (Purvin & Gertz, 1999) has estimated the energy required to meet the new regulations will be about 3,500 BTU/US gal. This assumed that existing technology is used to remove the sulphur. The US EPA took the approach that new technologies will be used that are more energy efficient and used a value of about 2,000 BTU/US gal. The EPA (1999) also looked at the technology considered by the CPPI and arrived at a similar number to the CPPI. We took a bottom up approach to each of the process units involved and arrived at a value of 2,900 BTU/US gal of gasoline. We calculated 1,200 BTU/US gal to make up for the loss of octane and 1,700 BTU/US gal for the desulphurization. This value of 2,900 BTU/US gal is used for the extra energy in the base year and the normal refinery energy efficiency improvement rates are applied to it as well so that by the year 2010 it is expected that the energy required will be only 2,580 BTU/US gal.

The more energy efficient technologies are not considered likely for most Ontario refineries because the Canadian regulations will require investments to be made before 2002 and the technologies will not be proven soon enough to allow them to be installed prior to the first stage of the regulation taking effect. Only one of the Ontario refineries can meet the 2002 standard today without any investment and is a potential candidate for the new technologies.

The low sulphur gasoline does have a number of positive impacts on greenhouse and non-greenhouse gas emissions. The US EPA (1998b) expects the emission rate for N_2O to be about 60% lower with the lower sulphur fuel. Emissions of non-greenhouse gases are expected to be 11-16% lower with the low sulphur gasoline for Tier 1 vehicles (EPA 1998). These reductions are incorporated in the model for the 2010 cases.

B.2.7 Typical Refinery and Crude Oil Inputs

The typical Ontario refinery has a capacity of 90,000-bbls/calendar day. It is running at 90% of capacity. The refinery has the capability of adjusting its gasoline output from 44% to 50% of capacity. The crude oil slate is mostly light sweet crude oil but some synthetic, heavy and bitumen is processed. The crude oil slate is shown in Table 4.1.

Table B-1 Typical Crude Oil Slate for Southern Ontario

Crude Oil Type	Percent of Input
Light Sweet	63
Heavy	18
Synthetic	12
Bitumen	7

It is assumed that the crude oil is produced in Western Canada and shipped by pipeline to the refineries. It is recognized that some of the crude oil now being supplied to these plants is offshore oil, but it is considered reasonable that offshore oil has a similar quantity of greenhouse emissions as estimated for Canadian crude oil.

The greenhouse gas emissions associated with the production of the crude oil is derived from the foundation paper for the upstream petroleum sector presented to the Industry Table of the National Climate Change Process (CAPP, 1998). The CAPP data was disaggregated by crude oil type and then combined in the same proportions as that used by the typical Ontario refinery. The numbers will be different than the Canadian average production because of this. The crude oil slate used here produces lower greenhouse gas emissions than the national average crude oil slate. The greenhouse gas emissions for the extraction of crude oil and the movement from Alberta to the Ontario refineries is shown in Table 4-2. The equivalent corn farming numbers are shown for comparison.

Table B-2 Greenhouse Gas Emissions for Crude Oil and Corn Production

	Oil Production	Corn Farming
Units	gram CO_2 eq/million BTU	Gram CO_2 eq/million BTU
Feedstock Recovery	8,219	8,912
Feedstock Transmission	371	1,588
Gas Leaks and Flares	1,921	0
Fertilizer Manufacture		6,654
Total	10,510	17,154

B.3 Refinery Energy Use for Conventional Gasoline and Ethanol Blends

The energy consumed in the refinery for gasoline production has been calculated for our typical refinery on a ground up, unit by unit basis. The total was then compared to the national average energy consumption as published by the Canadian Industry Energy End-use Data and Analysis Centre (Nyboer). The results compared very favourably and we have used our calculations for the total energy input into the model and CIEEDAC data for guidance on the proportion of each type of energy source that makes up the total. All Ontario activities benefit from the low carbon intensity of electric power generation in Ontario although this benefit will decline as more coal is projected to be used for electricity generation in future years.

The total energy used in the refinery is allocated to the various products produced on the basis of the energy actually used in each step. Products such as gasoline that go through multiple processes are assigned more energy than a heavy distillate that might only see one process step. This allocation of co-product credits is not the same approach used in the ethanol plant but it is consistent with approaches taken by others (Wang, 1999 and Delucchi, 1998).

The energy used to produce the gasoline in our typical refinery is 13,530 BTU/US gal for a base year of 1998. This has been adjusted to 14,090 for the model base year of 1996. It is recognized that refineries are reducing their energy inputs and we have reduced the energy consumption by 1% per year until 2001 and 0.5% per year after that until 2010. Delucchi does not take this systematic approach to energy efficiency in the refinery unlike most of the other fuel production

processes that he models. This approach was also taken in the Canadian version of the model (Levelton, 1999).

The energy input is for the maximum gasoline production rate, which is the most efficient, with some spare distillate capacity and an overall 90% crude capacity level. Ethanol not only replaces gasoline volume but it also adds octane to the gasoline pool. To take advantage of this octane a refinery has several options:

- Remove and sell other high octane material such as the aromatics benzene, toluene and xylene,
- Reduce the operating severity of the reformer, which is usually the refinery's lowest cost source of incremental octane,
- Increase gasoline production,
- Some combination of the above.

All of these options should result in lower energy consumption and essentially provides an energy credit to the ethanol. We have modelled the case of lower reformer severity, as there will be a limit to the amount of BTX that the market can absorb. For the base case, where the refineries are not limited by octane, we will give an energy credit of 590 BTU/US gal for a 10% ethanol blend. For the 6 and 8% ethanol blends, the energy credits will be 354 and 472 BTU/US gal respectively.

B.4 Description of Gasoline Distribution Network

The Ontario gasoline distribution system is an efficient network of pipelines, terminals, and truck transport. We have assumed that the gasoline component travels an average of 250 miles by pipeline and 75 miles by truck. The ethanol transportation has been previously described. We are using the model pioneered by Sunoco in Ontario where the ethanol is incorporated into the refinery blending system but is physically blended into the gasoline at one of the major terminals. This overcomes any potential problems with pipeline distribution of ethanol and the ethanol picking up too much water in the process. It is recognized that it is not the most energy efficient means of distributing the final blend.

B.5 Other Issues Associated with Use of Ethanol in Gasoline

The use of ethanol in gasoline increases the vapour pressure of the blend by approximately one-PSI. It has been assumed that the ethanol blends will have the same vapour pressure as gasoline and that the refinery will have to back out butane from the blends to insure that the fuel meets the specifications required. The interaction between ethanol and gasoline is non-linear and will result in the same amount of butane being backed out for a 6% ethanol blend as a 10% blend. If ethanol is used in all of the gasoline produced in the Ontario refineries about 4,100 BPCD[3] of butane will be backed out by the 20,500 BPCD of ethanol added. The butane may represent a challenge to some refineries, as the outlets for it are chemical markets and use as a fuel within the refinery. Neither of these outlets will have the same value as the use as a gasoline component. It may be possible to convert the butane to isobutane for use as alkylation feed but none of the refineries have a butamer unit in place today. Four of the five refineries have alkylation units.

[3] Barrels per calendar day.

Ethanol is soluble in water and only soluble in gasoline when it is dry so special attention needs to be exercised to keep the distribution system free of water. Ethanol is also a good solvent for some gums and tars that are sometimes found in gasoline systems. Ethanol can loosen these products and cause filters to be overloaded. The use of ethanol by Mohawk and Sunoco in Canada has demonstrated that these problems can be overcome. Ethanol use in the US is about 5.3 billion litres per year producing about 53 billion litres of ethanol blended gasoline, about 50% more than the amount of gasoline sold in Canada each year.

Appendix C
Glossary of Refining Terms

ALKYLATE. High-octane gasoline blending component produced in the refinery by a chemical reaction called alkylation. Basically, isobutane is chemically combined with olefins (e.g. propylene and butylene) in the presence of an acid catalyst to make the product. Normally, there are two types of alkylates used in gasoline blending. C3 and C4 alkylates with the C4 being higher octane and a better quality blending stock.

AROMATICS. Hydrocarbons characterized by the unsaturated benzene ring structure of carbon atoms. Common known ones are benzene, toluene, and xylene (BTX)

ATMOSPHERIC CRUDE OIL DISTILLATION. Commonly referred to as a Crude Unit. It is the refining process that separates crude oil into the various fractions by the use heat at atmospheric pressure in a large distillation column. The fractions usually consist of C4 and lighter, naphtha, light distillate, heavy distillate, virgin gasoil (VGO), and atmospheric tower bottoms. A specific temperature boiling range designates each of the fractions.

BARREL PER CALENDER DAY (BPCD). The maximum number of barrels that can be processed on average in 24 hours, 365 days of the year. This takes into account shutdowns, slowdowns, environmental constraints, scheduled downtime for routine maintenance and inspection, as well as unscheduled downtime such as mechanical problems and repairs.

BARREL PER STREAM DAY. The maximum number of barrels per day that can be processed at full equipment capacities under ideal conditions in any 24 hour period.

BENZENE. A high-octane, aromatic hydrocarbon that is produced mostly by the reforming of naphtha in a catalytic hydrogen reformer. It is considered highly carcinogenic and the amount allowed in motor fuel is limited.

BUTANE. A light hydrocarbon possessing high-octane properties but has very high vapour pressure and therefore has only limited use in the total blend. There are three different butanes; Normal butane, preferred in gasoline blending because it has a lower vapour pressure than isobutane. Isobutane, important feedstock for an alkylation unit. Butylene an olefinic hydrocarbon and an important feedstock for alkylation. All three butanes are produced during the crude oil refining process in varying amounts depending on the process.

CATALYTIC CRACKING. Common term referred to the Fluid Catalytic Cracking Unit (FCCU). The refining process of breaking down larger, heavier and more complex molecules into simpler, lighter and more valuable molecules. The process employs a solid fine catalyst that is fluidized and continuously regenerated.

CATALYTIC HYDROCRACKING. A refining process that uses hydrogen and a catalyst with relatively low temperatures and high pressures to convert middle to high boiling low value materials to higher value reformer feedstock and / or high grade fuel oils.

CATALYTIC REFORMING. A refining process that converts paraffins and naphthenes into high octane blending components by using precious metal catalyst in a hydrogen atmosphere at high temperatures and various pressures. The two common types of reformers are; Semi–Regen, this requires periodic shutdowns to regenerate the catalyst to maintain sufficient activity. Continuous, with a continuous regenerating reformer, the catalyst is maintained at peak activity level at all times.

FLEXICOKING. A thermal process cracking process which converts heavy hydrocarbons such as crude oil, tar sands bitumen, and heavy distillation residues into lighter hydrocarbons.

FLUID COKING. A thermal cracking process utilizing the fluidized-solids technique to remove coke for continuous conversion of heavy, low-grade materials into lighter products.

ISOMERIZATION. A refining process which changes the arrangement of atoms in the molecule without adding or removing anything from the original material. It is used to convert normal butane to isobutane and pentane (C5) and hexane (C6) into high-octane isopentane and isohexane.

MIDDLE DISTILLATES. A general classification that includes kerosene, kerosene- type jet fuels, diesels and distillate fuel oils.

MAXIMUM GASOLINE OPERATION. The refining can operate to maximize gasoline production or to minimize gasoline production. This flexibility allows changes to meet seasonal demand pattern shifts. For a typical refinery the difference between maximum and minimum gasoline can be up to 10% of the refinery crude charge depending on the type and gravity of the crude processed.

MAXIMUM DISTILLATE OPERATION. Normally, a maximum distillate operation goes along with a minimum gasoline operation. The flexibility noted under maximum gasoline heading is between gasoline and distillate. It is generally accomplished by altering the cut point of the two off the crude tower.

NAPHTHA. A generic term applied to a petroleum fraction with an appropriate boiling range between 121 degrees F. and 400 degrees F.

VACUUM DISTILLATION UNIT. A process of distillation at less than atmospheric pressure, which lowers the boiling point of the material being, distilled. Normal feed to the unit is atmospheric tower bottoms. Main products from the unit are light vacuum gasoil, catalytic cracker feed, and vacuum tower bottoms.

VISCBREAKING. A thermal cracking process in which heavy atmospheric or vacuum tower bottoms are cracked at moderate temperatures to increase production of distillate products and reduce the viscosity of the distillation residues.